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A Unequalven Clustering Routing Protocol in Wireless Sensor Networks

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Abstract

Because the uniform clustering algorithm has the problems of unbalanced and large energy consumption in long distance communication between clusters in Wireless Sensor Networks, we propose an Improved Unequalven Clustering Routing Protocol (IUCRP). To optimize the clustering mechanism, IUCRP takes residual energy, distance to the Sink node and density of surrounding nodes of the candidate cluster heads into consideration when calculates the competition radius of the node. Meanwhile, we employ the method of multi-hop routing between clusters and choose the next-hop by considering residual energy, distance and link cost factors to mitigate the "energy hole" problem. Simulations show that IUCRP can balance the network energy consumption and extend the network lifetime.

***Keywords**: Wireless sensor networks (WSNs), Energy-efficient, non-uniform clustering, routing*

1. Introduction

A WSN is a collection of wireless nodes with limited energy capabilities that may be mobile or stationary and are located randomly on a dynamically changing environment [1]. Since each sensor is limited in terms of processing capability, wireless bandwidth, battery power and storage space, in most applications, it is impossible to replenish power resources, a major constraint of WSN lifetime is energy consumption [2]. So how to effectively use the energy of sensor nodes, balance energy consumption of the network, prolong the network life time are hot issues in the experts' studies. While routing protocol is one of the most important factors that influences the energy consumption of Wireless Sensor Network, so the energy-saving feature of routing protocols has become one of the focuses nowadays.

Based on network structure, existing WSN routing protocols can be classified as flat or hierarchical. The hierarchical routing protocol is considered better and more suitable for applications in the large scale WSN. In hierarchical routing protocols, the whole network is divided into several clusters generally. There includes a cluster head node which is selected by an election algorithm and some cluster member nodes in each cluster. Cluster members will collect and send information to the cluster heads which aggregate, compress and send the information to the Sink node. Clustering is an effective technique for energy-saving. It reduces the amount of transmitted information via data compression, saves energy by using the Sleep/Wake mechanism and provides more scalability. As an active branch of routing technology, cluster-based routing protocols have proven to be effective in network topology management, energy minimization, data aggregation and so on [3]. But it brings new problems: the cluster head nodes close to the Sink node will die early due to excessive energy consumption of data forwarding. In order to solve this problem, some non-uniform clustering routing protocols have been proposed in literature,

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but there are still some questions.

2. Related Work

In recent years, many routing protocols for WSN have been proposed [4]. The Low-Energy Adaptive Clustering Hierarchy (LEACH) [5] protocol is a representative hierarchical routing protocol. It selects cluster heads randomly and keeps the network energy consumption balanced by periodical rotation of cluster heads to prolong the network life time. But in LEACH, data transmission over single-hop between cluster heads and Sink node will lead to large energy consumption. Some improved algorithms based on LEACH were proposed subsequently which optimize the clustering mechanism, but still did not solve the problem of excessive energy consumption of data transmission between clusters [6,8]. Multi-hop routing between clusters can save energy, but the cluster heads close to the Sink node will die early due to the large amounts of data forwarding tasks, which is called "hot spot" problem. In order to solve the problem, a non-uniform clustering algorithm Energy-Efficient Uneven Clustering (EEUC) [9] has been put forward, in which the network is divided into clusters of uneven size according to the distance to the Sink node, that is, the nearer to Sink node, the less cluster radius, in order for cluster heads to save energy for data forwarding and realize the network energy consumption balance. EEUC only considers the distance without considering the residual energy of nodes, the density of the surrounding nodes, and the energy consumption of transmission over a long distance between cluster heads. Based on EEUC, the protocol proposed that generates clusters of different sizes according to the location and the residual energy of the node [10]. At the same time, it takes the excessive energy consumption by long distance communication between cluster heads into consideration and uses the relay nodes which belong to both the clusters to shorten the communication distance and reduce energy consumption. But using the relay nodes to forward data may lead to the early death of the relay nodes which takes on too many tasks. Moreover, the forwarding path through the relay nodes is not fully aware of the link quality and link cost, which may increase network delay and the packet loss rate and lead to more energy consumption.

In this paper we present an improved non-uniform clustering routing protocol IUCRP, whose core is a non-uniform clustering algorithm. In the clustering algorithm, the clusters nearer to the Sink node, with less remaining energy, having more nodes around it will have smaller size in order that the cluster head can preserve energy for data forwarding and finally meet the requirements of energy balance and the extension of network lifetime. At the same time, IUCRP employs multi-hop communication between cluster heads to avoid long distance communication and prolong the network lifetime.

3. System Model

3.1. Network Model and Assumption

N sensor nodes are randomly scattered in a network which is an $M \times M$ square area S. We divide the network into clusters of various sizes. Cluster member nodes perceive and collect information from the sensor field, and send it to the cluster head. Cluster heads aggregate, compress and send the information in a multi-hop manner to the Sink node. The network model is shown in Figure 1.

Assume that the network model is as follows:

(1)Each node is randomly distributed in the monitoring area and has a unique ID.

(2)After deployed, the position of all nodes can’t be changed any longer.

(3)The Sink node is located in the external network. Its position is fixed and its energy is sufficient.

(4)All nodes can get their precise location and residual energy information.

(5)All nodes are homogeneous and they have the same initial energy, the same ability of perception, communication, data fusion. Their energy cannot be replenished.

(6)The communication link is symmetry. Transmission power of sensor nodes can be adjusted dynamically according to the distance.

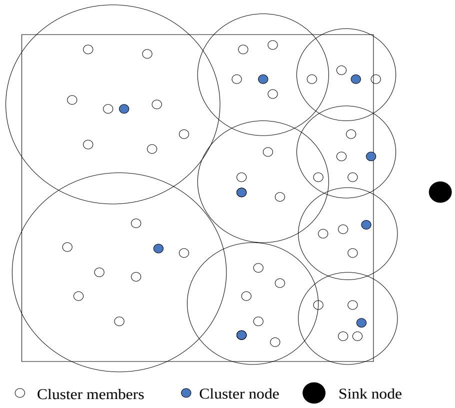

Figure 1. Network Model

3.2. Radio Model

We adopt the same power consumption model to calculate the energy consumption of the wireless communication as literature [11]. As shown in formula (1), $E_{Tx}(l,d)$, the energy consumption of the wireless communication module during the process of sending l bits data to destination to which the distance is d mainly lies in the transmission circuit loss and power loss. Under the condition of reasonable SNR ratio, the energy consumption $E_{Tx}(l,d)$ is shown as in formula (1):

$$E_{Tx}(l,d)=\begin{cases} lE_{elec}+l\varepsilon_{fs}d^2 & (d<d_0) \\ lE_{elec}+l\varepsilon_{mp}d^4 & (d\geq d_0) \end{cases} \quad (1)$$

In formula (1), E_{elec} means the energy loss of the transmitter or receiver circuit to send or receive every bit signal. When the transmission distance d is less than the threshold d_0, the radio power amplifier loss is calculated using free space model; when the transmission distance d is greater than the d_0, using multipath fading model. ε_{mp} means multiple of the signal amplifier; $\varepsilon_{mp}d^2$ and $\varepsilon_{mp}d^4$ mean radio power amplifier loss energy consumption by enlarging the transmission signal of per bit data in free space model and multipath fading model respectively. Threshold d_0 is determined as $d_0=\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$.

The node energy consumption in the process of receiving l bits data mainly lies in the receiving circuit loss, as shown in formula (2):

$$E_{Rx}(l) = lE_{elec} \quad (2)$$

In addition, the energy dissipated by data fusion for l bit data is E_{DA} and for l bits data is lE_{DA}.

4. The IUCRP Protocol

4.1. Formation of Clusters

In the network initialization phase, each node obtains its own location information. The Sink node broadcasts message in the entire network. Nodes calculate the distance between the Sink node and itself according to the position information of the Sink node in the received message. IUCRP uses a distributed cluster competition algorithm [12].

The cluster head are elected completely by local competition which is based on the residual energy of the nodes. Below is the detailed explanation of the algorithm. First of all, each sensor node generates a random number $t(t \in [0, 1])$. If the random number is less than the threshold T (T is predefined, denotes the proportion of candidate cluster nodes in the network), then the node will become a candidate cluster head, otherwise, it becomes a cluster member and sleeps until the cluster head election is finished. As described earlier, the goal of IUCRP is to make the clusters which are closer to the Sink node has less residual energy and dense nodes around it smaller. IUCRP achieves the goal by the control of the size of clusters using the competition regional of candidate cluster heads. We use R_{comp} to indicate the radius of the competition area and S_i to indicate any candidate cluster head. S_i computes its R_{comp} according to its distance to the Sink node, its residual energy and the node density around it. We use R_0 to denote the maximum competition radius of candidate cluster heads(here set R_0 to the maximum communication distance of sensor nodes). S_i determines its competition radius $S_i.R_{comp}$ by formula (3):

$$R_{comp} = [\varepsilon_1 \times (1 - c_1 \times \frac{d_{\max} - d(S_i, Sink)}{d_{\max} - d_{\min}}) + \varepsilon_2 \times \frac{E_{res}}{E_{init}} + (1 - \varepsilon_1 - \varepsilon_2) \times (1 - c_2 \times \frac{N_{neighbor}}{N})] \times R_0 \tag{3}$$

In formula (3), d_{max}、d_{min} represent the maximum and minimum values of the distance between sensor nodes and the Sink node respectively. $d(S_i, Sink)$ means the distance between S_i and the Sink nodes and c_1 is a constant between 0 and 1, which is used to control the value range. $(1\text{-}c_1 \times (d_{max}\text{-d}(Si,Sink))/(d_{max}\text{-}d_{min}))$ indicates that the closer to the Sink node, the smaller the radius of competition, thereby reduce the inner-cluster energy consumption of cluster heads near the Sink node and preserve energy for forwarding data between clusters. E_{res} means the remained energy of node S_i.E_{init} means the initial energy of the node. $E_{\mathrm{res}}/E_{\mathrm{init}}$ denotes that the more residual energy, the bigger competition radius in case that the cluster head which has less residual energy consumes too much energy and dies early. We use $N_{neighbor}$ to show the number of neighbors of S_i. N is the total number of nodes in the network. Here, $N_{neighbor}/N$ indicates the density of nodes around the candidate cluster head nodes and $c_2 \in [0, 1]$ is used to control the value range. $(1\text{-}c_2 \times N_{neighbor}/N)$shows that candidate cluster head's competition radius decreases linearly with the density of nodes around to avoid the cluster in which nodes are densely distributed having too many members and consuming more energy. ε_1、ε_2、$(1\text{-}\varepsilon_1\text{-}\varepsilon_2) \in [0, 1]$ are coefficients, depending on the weight of the 3 factors mentioned above respectively.

Each candidate cluster head S_i calculates its competition radius $S_i.R_{comp}$ by formula (3). After finishing computing its R_{comp}, S_i broadcasts Compet_Msg message to compete. Compet_Msg message contains the ID, residual energy RE and competition radius R_{comp} of S_i.

In the process of cluster heads competition, if S_i receives Compet_Msg messages from the other candidate cluster head S_j and at least one node between S_i and S_j is within the other's competition region, S_i will add S_j to its set of neighbor candidate nodes S_{ct}. Every candidate cluster head nodes S_i has a set of neighbor candidate nodes S_{ct} which consists of all candidate cluster heads having a competitive relationship with S_i constricted.

Competition process is as follows: if the residual energy of S_i is larger than any other node in its S_{ct}, S_i will become the final cluster head and broadcast Head_Msg message to announce for cluster head; if S_i receives the Head_Msg message from any other nodes in its S_{ct}, it will broadcast Quit_Msg messages and quit the election; if S_i receives Quit_Msg message from any other nodes in its S_{ct}, it will remove the node from its S_{ct}.

Before the end of the cluster head election process, the sleeping cluster member node will be awaked. Nodes selected as cluster head broadcast CH_Adv_Msg message. Cluster members join the cluster head after receive CH_Adv_Msg message from a cluster head. If a cluster member receives several CH_Adv_Msg messages, it selects the cluster head whose signal intensity is the largest to send Join_Msg messages to join. Cluster members join cluster heads and different clusters are established in the network.

4.2. Inner-Cluster Multi-hop Routing

In IUCRP, each node calculates the link cost between source node and destination node by confirmation message Hello_Msg which is sent to its neighbor node in a fixed time interval. The price of the path P which consists of a series of equipment D_1, D_2, D_3, ⋯, D_n and the corresponding link for D_i is [D_i, D_{i+1}] which is as formula (4) [13].

$$C(P) = \sum_{i=1}^{L-1} C([D_i, D_{i+1}]) \tag{4}$$

The C([D_i, D_{i+1}]) stands for the link cost, denoted by C (L), the calculation method as formula (5) :

$$C(L) = \min[\,7, round(\frac{1}{P_L^4})] \tag{5}$$

P_L is the probability of sending packets successfully by link L. C (L) reflects the times of retry needed to send a packet successfully via path L. In this paper, we use the link quality information (LQI) provided by the IEEE 802.15.4 MAC and PHY layer as basis. The relationship between LQI value and the link cost is shown in Table 1 [14].

Table 1. Relationship Between LQI and Link Cost

LQI	link cost
>75	1
50~75	3
<50	7

$$C_{sum} = \sum_{i=1}^{L-1} f_i(LQI) \quad , \quad f_i(LQI) = \begin{cases} 1, & LQI > 75 \\ 3, & 50 \le LQI \le 75 \\ 7, & LQI < 50 \end{cases} \tag{6}$$

Each node sends “hello” to its neighbor nodes periodically. After received “hello”, nodes extract LQI value and residual energy *ER*, and then calculate the link cost between the neighbor node and itself according to formula (6). Each node adds a field C in the neighbor table to record the link cost between the neighbor node and itself, and *ER* to record the residual energy of the neighbor node. At the same time, each cluster head node broadcasts a CH_Msg message in the range of δ times of competition radius of Si. After receiving CH_Msg message, if the neighbor Sj who sends the message is closer to the Sink node, Si calculates the distance between itself and Sj according to the signal intensity and the link cost between Sj and itself by formula (6). The information of distance and link cost mentioned above and residual energy of S_j will be recorded in the neighbor cluster header information table.

In IUCRP cluster head S_i uses the greedy algorithm to choose the relay cluster head S_r which has the minimum cost function in its neighbor cluster head set (including the cluster head nodes S_i itself). At the same time, in the process of transmitting data to the relay cluster head S_r, S_i uses the same method to choose cluster members as relay nodes. The cost function is defined as shown in formula (7):

$$P_{S_B} = \alpha \times \frac{ER}{EI} + \beta \times d(S_B, S_D) + \gamma \times \frac{1}{C} \tag{7}$$

EI is the initial energy of the nodes and is certain. $d(S_B,S_D)$ is the distance between source node S_B and destination node S_D. C stands for the link cost between the source node and the destination node.α、β、γ are the weights value of distance, remaining energy and link cost in the comprehensive weight respectively. By formula (7), we know that, in the inner-cluster routing of IUCRP, the closer to the Sink node, the more residual energy, the smaller link cost, the greater probability of the node can be selected as the next-hop.

4.3. Data Transmission

The whole process of transmitting the collected data to the Sink node can be divided into two stages: inner-cluster communication and intra-cluster communication. Cluster heads establish TDMA scheduling after the formation of clusters. Each cluster member sends the collected data to the cluster head within single jump in its time slot within cluster. After received data from cluster members, cluster heads aggregate the data and send to Sink node using inner-cluster multi-hop routing mentioned above.

5. Algorithm Analysis and Simulation

5.1. Evaluation Indicator

According to the special requirements for WSN routing algorithm and the optimization of IUCRP has for network performance, in this article we analysis and simulate the routing protocol IUCRP mainly from the four aspects, that is, the network lifetime, the end-to-end delay, the packet loss rate and residual energy of nodes.

5.2. Simulation Environment

We simulate LEACH, EEUC and IUCRP respectively by the simulation software OPNET 17.5 under the hardware environment of Windows 7 operation system, 2G memory. The network area is 100m*100m. 50 sensor nodes are distributed randomly and evenly in the monitoring area. The nodes have limited energy and cannot be recharged. Their transmitted power can be adjusted according to distance. The Sink node is located in a place a certain distance away from the network area and has abundant energy supply. IUCRP employs the 802.11 protocol in the MAC layer communication. The other simulation environment parameters this paper adopted are as shown in Table 2.

Table 2. The Simulation Parameter List

Simulation parameter	Value
Position of the Sink node	(150m,50m)
Node communication distance	50m
Initial energy	2J
E_{elec}	50nJ/bit
ε_{fs}	10pJ/bit/m^2
ε_{mp}	0.0013pJ/bit/m^4

5.3. Simulation Result and Analysis

(1) Network lifetime

This paper assumes that the node is dead if its energy is less than 0.002J. The network is dead if the number of nodes alive is less than 80% of the total number. When the number of nodes is 50, the change of survival node numbers of the three protocols are show as Figure 2:

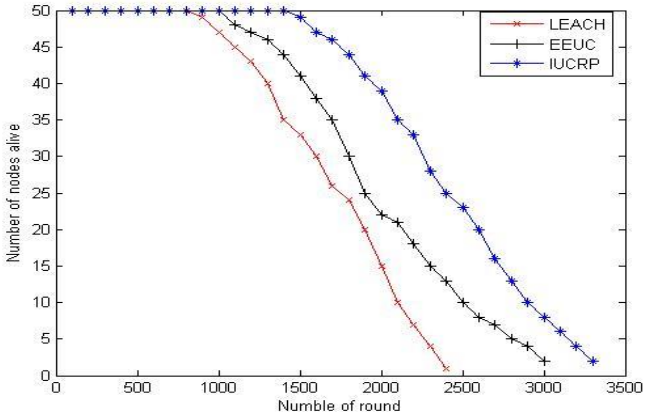

Figure 2. Network Lifetime

It can be seen from Figure 2 that the death time of the first node in LEACH is the earliest. This is due to that the cluster head nodes are randomly generated in LEACH not considering the residual energy. And cluster heads communicate with the Sink node through single hop consuming too much energy, leading to early death of some of the cluster heads. IUCRP has a large improvement in the performance of the network lifetime compared with EEUC. This is because that IUCRP considers not only the distance to Sink node but also the residual energy and the density of surrounding nodes in the process of clustering and of calculating. This makes the clustering more reasonable, reduces the energy consumption of cluster heads and puts off the death time of the first node. At the same time, IUCRP adopts the inner-cluster multi-hop routing which considers the distance, energy, link quality and link cost factor comprehensively to choose the next-hop which makes the network load balanced. Therefore, the network energy consumption of IUCRP is more balanced. And the death time of the first node is later. Nodes die more slowly.

(2)Energy consumption of cluster head in each round

We can see from Figure 3 that the energy consumption of cluster heads in each round in LEACH is the largest, the next is in EEUC and in IUCRP is the minimum. Because in EEUC and IUCRP cluster heads communicate with the Sink node by multi-hop routing avoiding large energy consumption by long-distance data transmission. At the same time, in the selection of cluster heads, IUCRP could make the energy consumption of cluster heads more balanced. Moreover multi-hop routing between clusters can reduce the energy consumption of cluster heads in inner-cluster communication, which makes the energy consumption of cluster heads in IUCRP minimum.

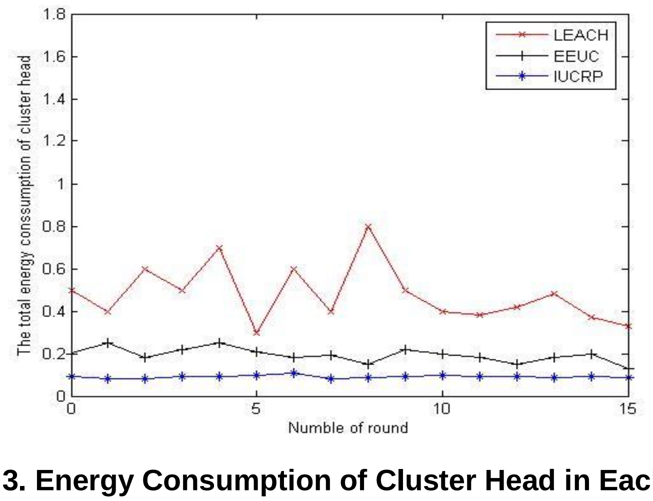

Figure 3. Energy Consumption of Cluster Head in Each Round

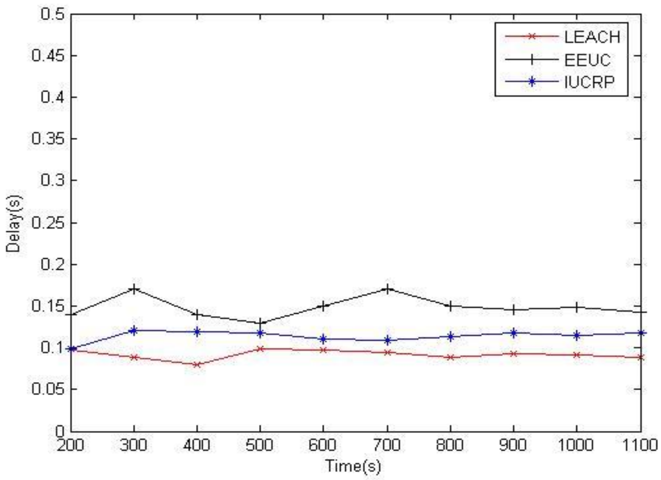

Figure 4. Network End-to-End Delay

(3) Network end-to-end delay

As is shown in Figure 4, the end-to-end delay in LEACH is the shortest. Because that cluster heads send data to the Sink node by one hop, the end-to-end delay is shorter correspondingly. And the end-to-end delay in IUCRP is shorter than in EEUC. This is because that in the process of data transmission between clusters in IUCRP, each node selects the neighbor node nearest to the destination node as the next-hop.

6. Conclusion

IUCRP considers the location information, energy and the node density factor in non-uniform clustering process, to effectively balance the network energy consumption. At the same time, the inner-cluster multi-hop routing considers the residual energy, link cost and link quality factors except for the geographical position when chooses the next-hop, which can not only increase the link utilization, but also shorten the time delay. Simulation shows that the improved algorithm IUCRP can effectively balance the network energy consumption and prolong the network life time. At the same time, it can increase the link utilization, reduce the packet loss rate and achieve the desired goal for improvement.

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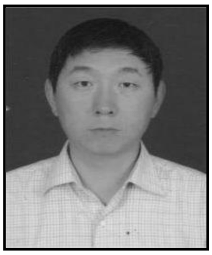

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