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Design and Analysis of an Efficient Approach of Cluster Head Selection for Balanced Energy Consumption in Wireless Sensor Networks

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Abstract

Since wireless sensor networks(WSNs) consist of massive tiny sensors for monitoring environmental data cooperatively and the energy resource of these nodes is non-replenishable, protocols should concentrate on communication and processing technologies with the minimum energy cost. To improve energy efficiency and maximize the network lifetime, some cluster-based routing protocols are presented. In those protocols, cluster heads selection could be regard as an important issue and it will affect the lifetime of the whole network. In this paper, we propose an efficient approach of cluster head selection for balanced energy consumption in WSNs based on sensor nodes' energy level and distance to the sink. Simulation results demonstrate our method can enlarge the life-time and balance the energy consumption well among all sensors.

***Keywords**: wireless sensor networks, energy consumption, cluster head selection, clustering*

1. Introduction

WSNs are often composed of massive cheap and resource-limited sensor nodes for monitoring physical or environmental data cooperatively, and the energy efficiency has become one of the hottest problems in recent years. Unlike traditional wireless ad-hoc network, the sensor nodes distributed in WSNs are usually kept in a static state and equipped with limited computing capability, memory, and battery power. Since it is particularly difficult to replenish the energy of the battery, how to achieve high energy efficiency and increase the network scalability are crucial research topics [4-5].

To maximize the lifespan of the whole network and achieve high energy efficiency, sensor nodes can be organized into clusters, which consist of member nodes and the cluster-head (CH) [6]. In this hierarchical architecture, data collected by member nodes usually are forwarded by CH node to the sink or base station (BS), and the the energy-efficient communication protocol LEACH (Low Energy Adaptive Clustering Hierarchy). On one hand, CH is responsible for communicating with its members. On the other hand, it should receive the sensed data of other sensors in the same cluster and transmit these data to the BS [7]. Because the energy consumption of the CH is higher than of other nodes, the cluster membership and the cluster-head (CH) are changed periodically by BS so as to balance the energy consumption and the quality of the CH selection will influence the network lifetime seriously. Based on this method, many clustering protocols are presented for optimizing the selection of cluster heads and maximize data communication.

The remainder of the paper is organized as follows. In Section 2, we briefly review related work. Section 3 describes the system model. Section 4 presents the detail of the new methodology for CH selection based on sensor nodes' energy level and distance to

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the sink (or base station). Section 5 shows the performance by simulations and compares it with LEACH and ECP [8]. Finally, Section 6 gives concluding remarks.

2. Literature Review

To improve the energy consumption from the arbitrary node to the sink, a wireless sensor network is organized by several clusters, which can reduce communication overhead in single-hop manner. In this way, the network's lifetime is extended and it is equivalent to increase the energy efficiency of the WSN. In [9], an optimal number of cluster-heads is proven to be existed to achieve minimum energy consumption in each round in clustering WSNs. It can't ensure that the number of cluster-heads is always equal to the optimal value owing to the random cluster-heads selection in LEACH. Meanwhile, the residual energy of candidate nodes is not taken into account and then the communication overhead in the network is not optimum [10-11]. Therefore, the nodes have more residual energy should be selected as a CH with more opportunities, which can balance the communication overhead among the sensor nodes and improve the lifetime of the network.

To improve LEACH method by changing probability, Inbo Sim *et al*. [12] proposed Energy Efficient Cluster Header Selection (ECS) algorithm, which take the probability function and energy parameter into consideration to choose optimal cluster heads. N.D. Tan *et al*. [13] proposed an LEACH-DE (LEACH- Distance Energy) routing protocol to decrease energy consumption and prolong network lifetime. During the process of CHs selection in LEACH-DE, residual energy of the nodes is classified into several levels and the geometric distance between the candidate nodes to the BS are examined for generating a key parameter. Both of those factors will influence the formation of clusters.

Minhas Akhtar [14] have extended the analytical model and present an Energy Aware Intra Cluster Routing (EAICR), which adopts multihop routing. Besides, several parameters are considered for CH selection, including number of packets sent in the network, energy consumed by the network, remaining energy level of nodes at specific time and network lifetime of the network.

O. Younis *et al*. [15] proposed a hybrid energy-efficient distributed clustering protocol, which attempts to deal with the CH selection problem based on a hybrid approach of the node's residual energy and the proximity distance between the node and its neighbors.

M. S. Ali et.al [16] proposed a novel scheme for cluster heads' selection, which defines current state probability and general probability of each node and employs approximation operators or priori information in each round. Sajjanhar *et al*. [17] proposed a Distributive Energy Efficient Adaptive Clustering (DEEAC) protocol, which focuses on the spatio-temporal variations of message transmission rates in different regions and determines the cluster head's selection according to node's hotness value and residual energy. B. Elbhiri *et al*. [18] proposed a Stochastic Distributed Energy-Efficient Clustering method (SDEEC) where the clusters are formulated in distributed manner and the cluster head election probability is more efficient and design a stochastic scheme detection to extend the network lifetime. Li, C. *et al*. [19] proposed an unequal clustering algorithm (EEUC), where the clusters far from the base station is larger In proportion than those close to the base station so as to balance the energy consumption of different cluster heads.

3. System Assumptions

We use the same "first order radio model" as presented in [20], in which the sensor nodes are equipped with transmitter and receiver antenna to obtain or amplify the transmission signals. A radio dissipates E_{elec} to run the transmitter or receiver circuitry, and the transmitter amplifier is E_{amp}. Thus, to transmit b bits message a distance d, the energy consumption can be calculated as:

$$E_{Tx} = \begin{cases} b(E_{elec} + \varepsilon_{fs} d^2) & d < d_0 \\ b(E_{elec} + \varepsilon_{amp} d^4) & d \geq d_0 \end{cases} \tag{1}$$

and to receive this message, the energy expends:

$$E_{Rx} = b * E_{elec} \tag{2}$$

All nodes in the network are divided into three types, including the CH, auxiliary cluster nodes and member nodes. Firstly, the CHs should be selected, and the characteristic of heterogeneous energy of each node is taken into consideration. For node i, we denote the set of neighbor nodes in range of radius R by S_i, and E_{res_i} is the residual energy. Whether the node i can be selected as CH or not depends on the ratio of its residual energy to the average energy of it neighbors. Assuming that p_i is the percentage of being selected as CH:

$$p_i = p_{opt} \times \frac{\sum_{j \in S_i} E_{res\_j} / |S_i|}{E_{res\_i}} \tag{3}$$

where p_{opt} is the optimal percentage, and it can be calculated as:

$$p_{opt} = \frac{k_{opt}}{N} \tag{4}$$

According to [21], the optimal number of CHs in the whole network is given as:

$$k_{opt} = \frac{\sqrt{N}}{\sqrt{2\pi}} \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{amp}}} \frac{M}{d_{sink}^2} \tag{5}$$

where d_{sink} is the mean value of all CHs to the sink, and $d_{sink} = 0.765 \frac{M}{2}$.

4. The Proposed Solution

4.1. Cluster Formation

Due to the impact of the nodes' energy on our system model, it is better to select the nodes with more remaining energy near the base station to reduce the energy consumption of nodes. By introducing the energy factor into the selection of the CHs, the improved threshold value can be expressed as:

$$T^*(n) = \begin{cases} \frac{p}{1 - p(r \bmod (1/p))} \times \left(\frac{E_{res\_i}}{\sum_{j \in S_i} E_{res\_j} / |S_i|} \right)^2, n \in G \\ 0, others \end{cases} \tag{6}$$

where r is the current round and G is the set of the sensors which have not been selected as CHs till the last rounds. E_{res_i} is the residual energy of node i, then $\sum_{j \in S_i} E_{res\_j} / |S_i|$ denotes the average remain energy of its neighbors.

If $E_{res\_i} > \sum_{j \in S_i} E_{res\_j} / |S_i|$, then $\frac{E_{res\_i}}{\sum_{j \in S_i} E_{res\_j} / |S_i|} > 1$ and it makes the value of $(\frac{E_{res\_i}}{\sum_{j \in S_i} E_{res\_j} / |S_i|})^2$ grows exponentially, and vice versa. Consequently, the value of $T^*(n)$ from the node which remains more energy is much larger and has the more possibility to be selected as CH.

According to the optimal probability p_{opt} , the whole network can be divided into k_{opt} equal regions. In conventional deployment stage, the CH only is responsible for aggregating the data collected from it memberships with the range of its region and then relay the aggregated solution to sink. Besides, the neighbor nodes of sink will perform direct transmission to the destination. In this paper, we assign a random initial energy level to each sensor after cluster formation. To balance the energy consumption of all nodes, the definition of energy levels is presented and used for selecting the CH-candidate nodes, which transmit packets and advertises its ID and residual energy level. A CH-candidate monitors advertisements from others and defers from acting as a CH if a higher energy level is reported by another. Finally, candidate with the highest residual energy level will become CH. Other nodes in this region will become the member of this cluster.

4.2. Selection of CH-Candidate Nodes

In the secondary stage of the election of CH-candidate nodes, the circumstances can be divided into two different situations. In the model of single hop, when the distance between the CHs and the sink meets with $d \geq d_0$, the CHs are responsible for collecting and aggregating the sensing data and the CH-candidate nodes forward this solution to the sink. However, in the multi-hop mode, while the distance accords with $d \geq \frac{1}{2} d_0$, the CH-candidate nodes will fulfill the task of collecting the data by the member nodes in same cluster, and at this point, the CH is responsible for forwarding the fusion data to the next CH near by sink.

In case of single-hop routing mode, if the distance between the CH and the sink node is greater than or equal to d_0 , then the CH-candidate nodes should be selected. To optimize the lifetime and decrease the energy consumption during the process of data relay, the selection of CH-candidate nodes are considered from three aspects, *i.e.* the residual energy E_{res_i} , the distance between the node and CH $d(i, CH)$, and the distance from node to the sink. Normally, the nodes with higher residual energy, nearer by the CH, or the distance from CH-candidate nodes less than those should be chosen. Therefore, the formula for selecting the appropriate CH-candidate nodes is shown as follows:

$$j = \arg\max_{j \in S_{CH-i}} \{ \frac{d(CH_i, sink) - d(j, sink)}{d(j, sink)} \times E_{res-j} \} \quad (7)$$

where $d_{CH_i - sink}$ denotes the distance between CH i and the sink.

4.3. Intra-cluster Multi-hop Routing Setup

In multi-hop communication, the task of CH receives the data from the various member nodes of the cluster, aggregates all the data and then sends the data to the next hop and forwards messages from neighboring cluster head. In this paper, a multi-hop communication protocol is designed to save energy. We set a value d , which is the threshold for judging the data will be transmitted to CHs directly or not. If the distance is farther than d , it will find an adjacent node as the relay one. Otherwise, it can forward the data to the destination directly. In addition, the selection of relay node depends on the distance and residual energy. According to the free space propagation channel model, the energy consumption and the energy consumption for forwarding node i to node j are defined respectively as follows.

$$\begin{cases} E(i,j) = 3lE_{elec} + l\varepsilon_{fs}(d(i,j)^2 + d(j,CH)^2) \\ E_{forward}(i,j) = d(i,j)^2 + d(j+CH)^2 \end{cases} \tag{8}$$

Since the CHs near the sink are responsible for forwarding the data both of theirs and remoter clusters in traditional multi-hop communication, it will result in the consequence that the nodes near the sink become invalid earlier than the remote and cause network segmentation. We resolve this problem by introducing the relay node to avoid the nodes near CHs depleting their energy quickly. The cost function is defined as follows.

$$cost_j = \delta \times \frac{d(i,j)^2 + d(j+CH)^2}{\max_{i,j \in S_{CH}}\{d(i,j)^2 + d(j+CH)^2\}} + (1-\delta)\frac{\max\{E_{res\_j}\} - E_{res\_j}}{\max\{E_{res\_j}\}} \tag{9}$$

Where δ is a parameter and $0 < \delta < 1$.

After each node has chosen the minimum cost node as its relay node, an intra-cluster route is constructed.

5. Simulation

In this section, we evaluate the performance of our protocol implemented with MATLAB [22-23]. For simplicity, we assume the probability of signal collision and interference in the wireless channel is ignorable. The parameters of specific experimental are shown in Table 1.

Table 1. Experimental Parameters

Parameters	Value
Simulation area(m×m)	400×400
Number of nodes	200
The station of BS	(200,200)
Initial energy	2J
ε_{fs}	10PJ/bit.m^2
E_{elec}	50nJ/bit
ε_{amp}	0.0013PJ/bit.m^4
D_0	90m
δ	0.4

In this section, we study the proposed algorithm, concentrating on the number of active nodes over time, the number of messages received by sink and the distribution of the average energy consumption of all nodes. And we define whether sensor node is considered as active or not depends its existing energy is greater than 0 and also can communicate with its adjacent nodes within given range. As a result, it can be deduced that few CHs die quickly for improper load balancing in contrast that sensor nodes may be unable to communicate with its belonged CH even with some existing energy.

As shown in Figure 1, the number of active sensors in each round varies and our proposed method can obtain the longer lifetime than others along with the operation of the network. In LEACH, the difference of nodes' initial energy is not taken into account during the phrase of cluster head's selection, the energy consumption of all nodes can be distributed unbalancedly, which influence the overall lifetime. Hence, it can be observed from the test that our protocol improves the lifetime by 18.3% compared with LEACH and 11.2% compared with ECP. Also, since ECP adopts data fusion processing and multi hop forwarding mode, it can decrease the transmission overload from sensors to sink and more active nodes exists than LEACH.

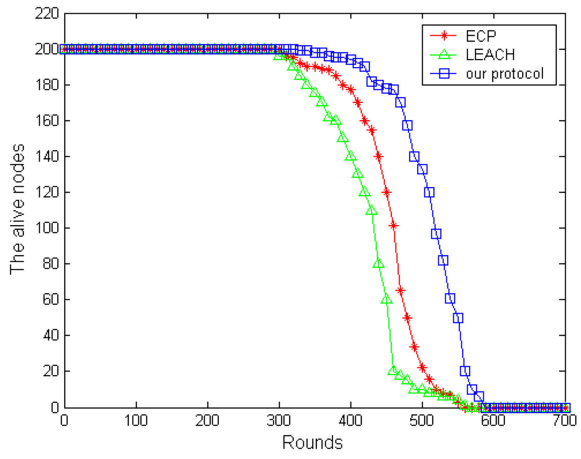

Figure 1. Number of Active Nodes Over Time

Figure 2 shows the information received by the sink and it is clear from the figures that total number of packets received by the base station in case of proposed protocol is much greater than other algorithms.

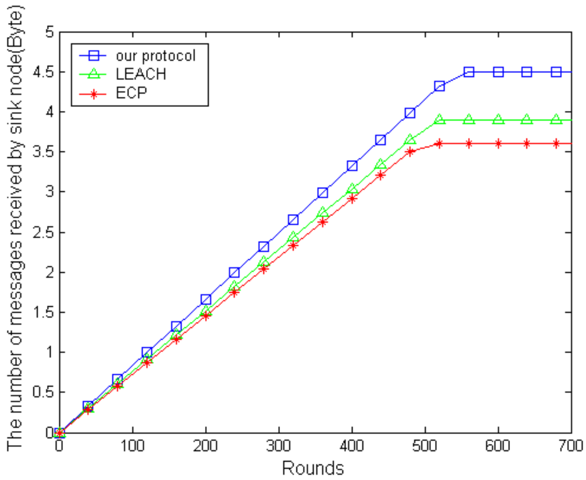

Figure 2. The Number of Messages received by Sink Over Time

The distribution of the average energy consumption of all nodes with respect to the number of rounds for each algorithm is shown in Fig. 3. The simulation results show that in our protocol the average energy consumption of all nodes varies comparative stably during the most of the rounds. The average energy consumption of other algorithms fluctuates in wide range, especially in LEACH. On the other hand, the average energy consumption of ECP can keep in the low level, which benefit from the optimization of the selection of CHs.

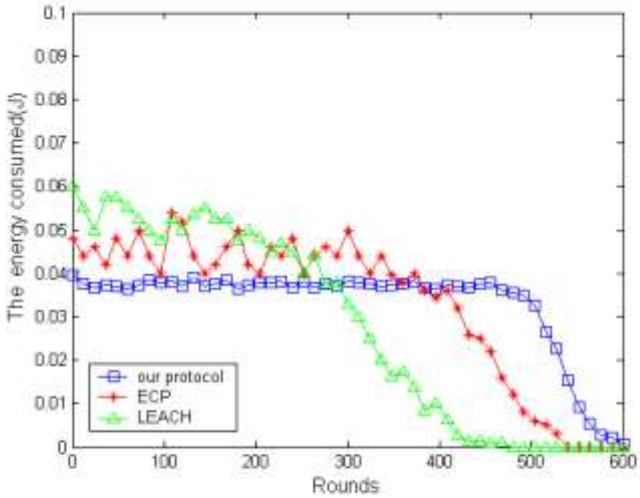

Figure 3. The Distribution of the Average Energy Consumption of all Nodes in Different Rounds

6. Conclusion

By analyzing the deficiency LEACH clustering algorithm, this paper proposes a candidate cluster head selection mechanism for energy balancing. The main idea is the classification of nodes according to the residual energy for the sake of that the node with higher level are more likely to be cluster-head. In addition, for the non-cluster head nodes, they may receive the messages from multiple candidate cluster heads and choose to join the cluster according to the comprehensive evaluation of residual energy and distance. In order to make the energy consumption more balanced, the cluster-heads send the data to the sink in the manner of multi-hop transmission, and use unequal clustering mechanism to avoid the situation where the nodes near the sink deplete their energy much faster than distant nodes.

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