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An Energy Efficient Multi-hop Cluster-Head Election Strategy for Wireless Sensor Networks

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Abstract

According to the double-phase cluster-head election method (DCE), the final cluster heads (CHs) sometimes are located at the edge of cluster. They have a long distance from the base station (BS). Sensor data is directly transmitted to BS by CHs. This makes some nodes consume much energy for transmitting data and die earlier. To address this problem, energy efficient multi-hop cluster-head election strategy (EEMCE) is proposed in this paper. To avoid taking these nodes far from BS as CH, this strategy first introduces the distance from the sensor nodes to the BS into the tentative CH election. Subsequently, in the same cluster, the energy of tentative CH is compared with those of other nodes, and then the node that has more energy than the tentative CH and being nearest the tentative CH are taken as the final CH. Lastly, if the CH is located at the periphery of the network, the multi-hop method will be employed to reduce the energy that is consumed by CHs. The simulation results suggest that the proposed method exhibits higher energy efficiency, longer stability period and better scalability than other protocols.

1. Introduction

The wireless sensor network (WSN) consists of a good deal of microsensors used in many detection areas [1], forming the network in a self-organizing manner and transmit the sensory data to data collection center. As fueled by the continuous advancement of microelectronics technology, a growing number of WSNs are used in smart home, environmental monitoring, battlefield enemy detection [2], etc. Duo to the limitations of sensor nodes and the external conditions of deployment, they have limited energy and made recycle or recharge process difficult to achieve [3,4]. How to improve the energy efficiency of each sensor and extend the network life cycle is the goal pursued by many researchers in recent years [5].

Based on detection capability, sensor nodes can be split into different categories communication range and energy, etc. The homogeneous WSN is made up of the same type of sensor [6]. In contrast, the heterogeneous WSN comprises different types of sensor. In the energy heterogeneous WSN, each sensor node has different the initial energy for different type sensor nodes, requiring a more reasonable

mechanism to assign the corresponding network load for each sensor node according to the energy [7].

The routing method performance is important for improving the WSN performance. The clustering structure is adopted by most routing algorithms [8], in which the cluster head (CH) nodes and the cluster member (CM) nodes are included. The role of the CH nodes is to aggregate the data of the CM nodes in the identical cluster and forward them to the base station (BS). The CM nodes primarily account for detecting environmental data and sending it to its CH node. Though over the past few years, to improve WSN's performance, many routing protocols have been proposed, there are still many areas that require improvement [9].

In this paper, an energy efficient multi-hop cluster-head election strategy (EEMCE) is proposed. The new algorithm not only pays more attention to addressing the CH nodes edge problem, but also makes a more comprehensive consideration in the CH replacement process and selects nodes closer to the BS and closer to the cluster center position as the final CH. In the meantime, the EEMCE algorithm uses a multi-hop method to transmit sensor data for the CH node that has a long distance from the BS to reduce its energy that is consumed for transmitting data.

The subsequent work arrangements are presented as follows: Section 2 gives the relevant work; Section 3 introduces the network model; Section 4 describes the newly proposed algorithm in detail; Section 5 presents the simulation comparison result; the last section draws the conclusion.

2. Related Work

In past years, there has great progress in the research of WSN protocol, and the proposed clustering algorithm has exerted a cross-stage impact on the improvement of routing algorithms.

The LEACH [10] protocol refers to a classic clustering routing algorithm for homogeneous WSN. It selects the CH nodes according to the probability threshold; other normal nodes will join the cluster closest to itself after the CH node is generated. The HEED [11], TEEN [12], BEEM [13], and EEUC [14] protocol have all evolved on that basis. The SEP [15] protocol is also an iconic algorithm for heterogeneous WSN. It splits the energy of a node into two levels (the advance node and the common node). Each type of node has threshold conditions for the respective elected CH nodes. Unlike the SEP [15] protocol, the DEEC [16] protocol constructs a multi-layer energy heterogeneous model, which selects the CH node according to the ratio of the average energy of the whole network to the current energy of the sensor node, to achieve better network scalability. The DDEEC [17] protocol adopts a new energy threshold conditions for each sensor node in order to make CH elections more rational. When the residual energy that the sensor node has is larger than the threshold condition, it will have a greater probability for the advanced node being elected as a CH node; nevertheless, the energy of the node is less than the condition, each node has the same probability of becoming a CH. In the smart grid, to better play the performance of WSANs, the study [18], through the comparison and analysis between different algorithms, finally finds that the ISMA protocol has less delay and maximum throughput compared with other algorithms. The EACBM [19] protocol proposes a multi-hop routing algorithm based on energy perception. It uses sub-clusters to forward data from nodes in areas that are not perceived by the CH, which greatly improves energy efficiency. The EE-MRP [20] protocol splits the detection area into multiple parts, which makes the CH distribution more uniform, reduces the cluster reconstruction rate, and improves the throughput and life cycle of the network. The LAR-CH [21] proposes a load-based CH

rotation mechanism. The algorithm exploits the residual energy that the sensor node has to determine the dynamic threshold of the CH rotation, thereby reducing the premature death of the CH and extending the life cycle of the WSN. The LEACA [22] protocol proposes a fixed cluster structure formed at the beginning phase of the network operation, which reduces the amount of CH changes and the energy consumption of rebuilding the cluster, which extends the network life cycle compared with traditional algorithms. The D2D discovery maximization (D2D-DM) iterative algorithm [23] is proposed, in which the transmission mode is dynamically adjusted between the half-duplex and in-band full-duplex modes according to the variation of the signal-to-noise ratio. In the meantime, an open-loop power control mechanism is proposed for users with limited power. Compared with conventional static resource allocation and the random back off schemes, the proposed algorithm significantly increases the number of discovered users. In [24], the development and current status of PS-LTE are introduced. In the meantime, a disaster recovery architecture DR-PSLTE is proposed. The architecture consists of a software definition network, a UAV cloudlet layer and a wireless access layer, reducing latency and power consumption via centralized and distributed processing.

The DCE [25] is a distributed heterogeneous two-stage CH election wireless sensor routing protocol based on cluster structure. In the first stage CHS election, the tentative CH node is selected according to the relative probability level of residual energy and the initial energy that the node has. In the second stage, if the cluster members of a tentative cluster have more residual energy than the tentative CH, the CM node with more energy than tentative CH will broadcast, which will replace the tentative CH to become the final CH node. Though the DCE protocol improves the way of CH elections and improves the stability period of the network, we find that CH marginalization may occur after the DCE protocol CH replacement in the actual operation process, which is not conducive to the effective network energy. Besides, in the DCE protocol, the CH directly transmit the collected sensor data to BS in the data transmission phase. It will consume larger energy if the CH has a long distance from the BS.

The newly proposed algorithm is based on the DCE protocol and proposes improvement measures for the CH marginalization problem and the excessive energy consumption of the peripheral CH in the data forwarding process, which will be discussed in detail in the following sections.

3. Energy Heterogeneous Network Model

In this section, the N sensor nodes are randomly deployed in a $M{\times}M$ detection area, and the sensor nodes can transmit sensor data to the BS. The network adopts a clustering structure, in which the CHs collect the data of cluster members and subsequently aggregate and transmit the aggregated data to the BS by the multi-hop mechanism. According to the different distance for the receiver and transmitter, the multipath channel model and the free space dissipation model are used respectively. The energy required to transmit l bit data through do is:

$$E_{TX} = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 & \text{if } d \le do \\ lE_{elec} + l\varepsilon_{mp}d^4 & \text{if } d > do \end{cases} \tag{1}$$

If it receives l bit data, the energy that is consumed by receiving l bit data can be expressed as

$$E_{RX} = l \times E_{elec} \tag{2}$$

where E_{elec} denotes the consumed energy for the receiver receiving l bit data or the transmitter sending l bit data depending on digital coding, modulation, demodulation, signal propagation and filtering, etc. ε_{mp} and ε_{fs} represent the energy consumed by free space amplifier and multipath channel amplifier, respectively. do is the distance threshold that sensors adopt different channel models.

The new algorithm uses a multi-level energy heterogeneous network in which the initial energy of each sensor is between $[E_0, E_0(1+a_{max})]$, where a_{max} denotes the upper limit of the energy heterogeneous factor. The $E_0(1+a_i)$ denotes the initial energy for i node, where a_i denotes the a_i times more energy than E_0. Therefore, the total energy in the whole network for all sensor nodes can be expressed as

$$E_{total} = \sum_{i=1}^{N} E_0(N + a_i) = E_0(N + \sum_{i=1}^{N} a_i) \tag{3}$$

The newly proposed algorithm is adapted to the following network environment:

- Once deployed, all nodes are not mobile and the battery of all nodes cannot be charged and replaced.
- All nodes have their unique ID number and the ability to calculate, store, aggregate, and forward.
- All sensor nodes can obtain the distance information with other sensor nodes based on the signal strength of received signal and acquire their own residual energy.
- Each sensor node can automatically adjust the reception and transmission power on the basis of the distance information.
- The maximum emission power of the node can ensure the communication with all nodes (including BS) in the network.

4. Proposed Protocol

In this part, we detailed introduce the new proposed method. The ultimate aim of the proposed method is to improve network stability, scalability and energy efficiency. To make it be easier to understand, we divide the algorithm into two phases that are data transmission phase and CH election phase in every round.

The routing algorithm of LEACH-like mostly uses the method in (4) to election some sensor nodes as CHs.

$$T(S_i) = \begin{cases} \dfrac{p_i}{1 - p_i (r \bmod \dfrac{1}{p_i})} & \text{if } S_i \in G \\ 0 & \text{if } S_i \notin G \end{cases} \tag{4}$$

where S_i denotes the ith node, $T(S_i)$ is the threshold that is used to select CH, p_i is the probability that the sensor node S_i becomes the CH, r is the round number, G is a set that consists of sensor nodes that have not been selected as CH in the $1/p_i$ round.

All sensor nodes randomly generate a number that is between [0, 1] in each round. If the value of random number is smaller than the threshold that is shown in (4), then the node will be selected CH. Due to the randomness, it is inevitable that some unsuitable nodes will be selected as CHs, which will reduce

the overall performance of the WSN. To overcome the problem, we divide the process of CH election into tentative CH election and final CH election.

4.1 Tentative CH Election Phase

The initial energy is different for different sensors types in energy heterogeneous WSN. The DCE protocol introduces the average energy of network and residual energy of sensor node into the probability that a sensor node becomes CH node, which is expressed as:

$$p_i = P_{opt} \times \frac{(1+a_i) \times E_i(r)}{(N + \sum_{i=1}^{N} a_i) \times \overline{E}(r)} \tag{5}$$

where N is the number of sensor nodes. $E_i(r)$ and $\overline{E}(r)$ respectively denote the current energy of ith in the rth round, the average residual energy of all nodes in the rth round and shown in (6), a_i is the heterogeneity factor of lth node

$$\overline{E}(r) = \frac{1}{N} E_{total}(1 - \frac{r}{r_{max}}) \tag{6}$$

The effect of sensor nodes position on CH position is not considered in the DCE method, so some sensor nodes farther from the BS may be become CHs. If the CH has a very long distance from the BS, the CH will consume much more energy to transmit collected sensor data to BS. It is limited for the energy of sensor nodes. This will shorten the survival time of the sensor node that is selected as CH. To address these problems, we introduce the distance between the BS and sensor node to (5), to avoid using the sensor nodes that have long distance from BS as CH. The proposed probability is shown as

$$p_i = p_{opt} \times \frac{(1+a_i) \times E_i(r)}{(N + \sum_{i=1}^{N} a_i) \times \overline{E}(r)} \times \frac{1}{d_i} \tag{7}$$

where d_i represents the distance from ith sensor node to the BS.

4.2 Final CH Election Phase

In the traditional CH election, if the random number that is generated by sensor node is smaller than some threshold, the sensor node will act as CH. Since the above random number is generated randomly for sensor node, the generated number may be very small for the sensor node with lower energy. Therefore, it is inevitable that some nodes that have smaller residual energy are selected as the CH at some times. It will cause some nodes to die prematurely, which negatively affects the stability of the network.

In the DEC protocol, when the tentative CH nodes are selected, they broadcast to the detection area. If the ordinary nodes receive the information, they will join the corresponding cluster based on the received tentative CH information and received signal strength (RSS). In the meantime, the ordinary nodes in each cluster will compare their energy with its tentative CH; if an ordinary node has more energy than tentative CH, this ordinary node will broadcast to all sensor nodes. If the broadcast is successful, it will be selected as the final clusters head to instead the tentative CH. The other nodes in this cluster will stop competing of CH and join the new cluster as an ordinary node.

In the actual operation process, the DEC protocol does not ensure that the new CH remains still placed at the original cluster center. Fig. 1 suggests that the node M and H replace respectively, the original CH node A and B; it obvious that the distance between node J and K to the new CH M has increased. The distance of nodes K and C reaching the neighbor CH H is closer than to M, which will consume more energy for K and C nodes transmitting data to their corresponding CH.

To avoid the problem that final CH may be located at marginalization, we introduce the current energy of nodes, distance from the nodes to tentative CH into the election of final CH. Firstly, we compare the energy of tentative CH with all nodes in the same cluster and mark the nodes with more energy than tentative cluster. Secondly, we select the sensor node the nearest to the tentative CH as final CH from the marked sensor nodes.
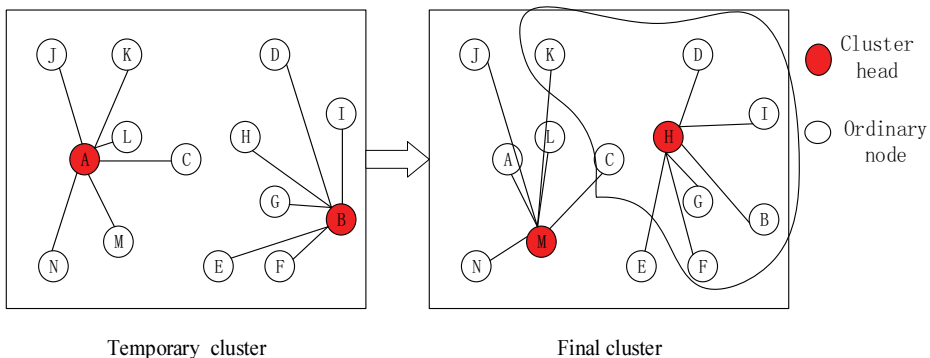

Temporary cluster   Final cluster

Fig. 1. Tentative cluster and final cluster for DEC protocol.

To further explain our proposed method. A tentative cluster is constructed, consisting of tentative CH and ordinary nodes. Supposing the C, B, and E nodes have more energy than the tentative CH A, and other nodes have smaller energy than the tentative CH A in the cluster, as shown in Fig. 2(a). We firstly mark the nodes that have more energy than tentative CH, suggesting that we mark the C, B and E nodes in Fig. 2(b). Secondly, we compute the distance between the C, B, and E nodes and the tentative CH, and then select the node with minimum distance as final CH. In the Fig. 2(b), it is suggested that the node B is the nearest the tentative cluster node, so we use the node B as the final CH. It is shown in Fig. 2(c). The CH B is near the center of cluster, which will make a balance between energy expenditure and time that network is survival.
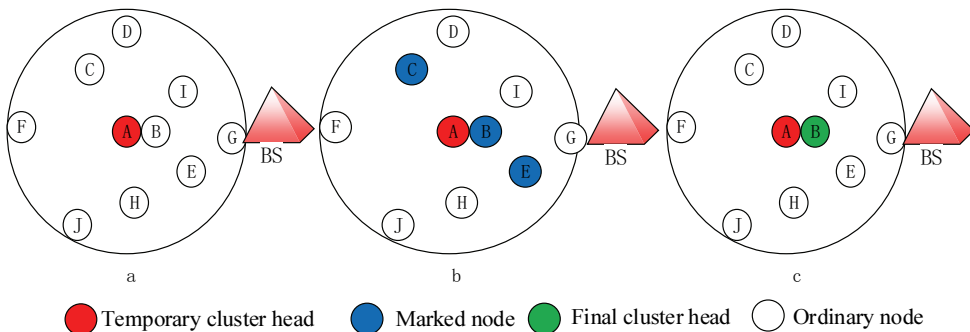

Fig. 2. The schematic diagram about the election of final CH for our proposed protocol.

In DCE protocol method, it randomly selects a node to compare the energy with tentative CH, if the selected node has much more residual energy than the tentative CH, and the selected node will be directly used as final CH. Therefore, in the Fig. 2, the node C, B, and E all may be selected as final cluster for DCE protocol. If the first compared node is node C, the node C will be taken as final cluster for DCE protocol. From Fig. 2, it is suggested that the node C is not in the center of cluster, much energy will be consumed for other nodes sending sensor data to the CH. This will reduce the lifetime of nodes far away from CH and shorten the lifetime of network.

After the CHs election is achieved, the new CHs will broadcast the information to the entire wireless sensor network. The other sensor nodes will receive the broadcast information and send the join information to the new CH in original cluster. After the information is received, the new CH will allocate the communication time slot for each CM according to the TDMA (time division multiple access) mechanism. The new cluster is created.

4.3 Data Transmission Phase

When the new cluster has been established, the sensor nodes transmit sensor data to their CH node according to the allocated time slot in the same cluster. In DCE Protocol method, the CHs directly send the received data to BS, which will consume larger energy if the CHs have a very long distance from the BS. To make the energy consumption balance, the multi-hop is introduced to data transmission. Firstly, we compute the distances that are between the current CH and other CHs in the communication range of current sensor node. It supposes that the distance between the current CH and CH i is d_i, and the distance between the CH i and BS is l_i, and the distance between the current CH and BS is f_i. If $d_i < f_i$ and $l_i < f_i$, the CH i will be considered one of the CHs between the current cluster and BS. Secondly, if there is other CHs between the current CH and BS, the sum of energy consumption should be computed for each possible route, and the route with minimum energy consumption should be taken to send data. If there is no any CH between the current CH and BS, the current CH directly sends to BS.

4.4 Difference between the Proposed Method and Other Methods

Duo to each sensor node has different initial energy during the deployment phase for energy heterogeneous wireless sensor networks, so it is important to reduce energy that is consumed by the network to extend survival time for network. Most of the existing algorithms (DEEC protocol, DDEEC protocol, SEP protocol, etc.) generate new CH nodes by comparing the random values generated by the nodes with the threshold conditions in the iterative process. The CH thus is generated randomly, and some nodes that have lower-level residual energy have the same probability to be selected as CHs, causing some sensor nodes in the network to die prematurely. Therefore, a more reasonable CH selection scheme is necessary.

We propose an EEMCE strategy based on the DCE protocol. The new algorithm can not only ensure that the nodes which have larger energy in each cluster structure are selected as CHs to undertake more networks tasks, but also improve the shortcomings of the DCE protocol.

The main differences between the proposed method and DCE method are given from three aspects. (1) For electing the tentative CH, it does not consider the distance from the sensor nodes to the BS, which makes some sensor nodes that have a long distance from the BS be selected as the tentative CH and

generates higher transmission energy consumption in the DCE protocol method. For our proposed EEMCE algorithm, it is not only to consider the residual energy of the nodes but also the distance that the nodes between the BS, so that those nodes that are closer to the BS and have larger residual energy are selected as tentative CHs. This will decrease energy expenditure for transmitting data to the BS by the cluster head node. (2) In final CH election phase, the DCE protocol method ignores the impact of sensor node location on network performance during the CH replacement process, which will cause the newly generated CH marginalization problem, and make the average transmission energy expenditure of the CM increase. The newly proposed EEMCE algorithm introduces the distance that is about the tentative CHs and sensor nodes when selecting the final CH nodes, which ensure that the newly generated CH have smaller distance to the cluster center position. So the proposed method makes the average transmission energy expenditure of the CM node in the cluster reduce. (3) For data transmitting, the all CHs directly transmit received data from sensor nodes that is in the same cluster to the BS in the DCE protocol method. When a CH node has a very long distance from the BS, it will consume much more energy. The EEMCE method uses multi-hop mode to select the routing path. This can avoid the CH that has a very long distance from the BS consuming much energy, and further more prolong the lifetime of CH.

5. Simulation and Discussion

We use the MATLAB software to simulate the proposed algorithm (EEMCE) and compare it with the DEEC protocol and the DDEEC protocol and the DCE protocol on the stability cycle of the network, the total number of data packets, energy consumption, and scalability, etc. We randomly deploy 100 sensor nodes in a square region with 100 m×100 m, where the energy heterogeneity factor a_{max}=1, and the position of BS is placed at the detection region center. Other simulation parameters are listed at Table 1.

Table 1. Parameters used in the following simulations

Parameter	Value	Parameter	Value
E_o	0.5 J	ε_{fs}	10 pJ/bit/m^2
E_{elec}	5 nJ/bit	ε_{mp}	0.0013 pJ/bit/m^4
E_{DA}	5 nJ/bit/message	Data	4000 bits
do	87.7 m	CM	16 bits

The relationship curves that are about the running round and the number of alive node for different methods are shown in Fig. 3. Fig. 4 shows the number of rounds for the first node dead, the half node dead and all nodes dead. From Figs. 3 and 4, it is suggested that the first node death of the new algorithm (EEMCE) appears in 1627 rounds, the DCE, DEEC, and DDEEC protocol appear in 1540 rounds, 1234 rounds, and 1237 rounds, respectively, revealing that the stability period of the new algorithm increases by 5.6% compared with DCE protocol. All nodes death occurs in 3560 rounds, 2609 rounds, 2897 rounds, and 3148 rounds for EEMCE, DCE, DEEC, and DDEEC protocol, respectively. Compared with the DCE protocol, the network life cycle of EEMCE protocol is extended by 36.5%, revealing that the new algorithm EEMCE has a longer stabilization period and network life cycle than others.
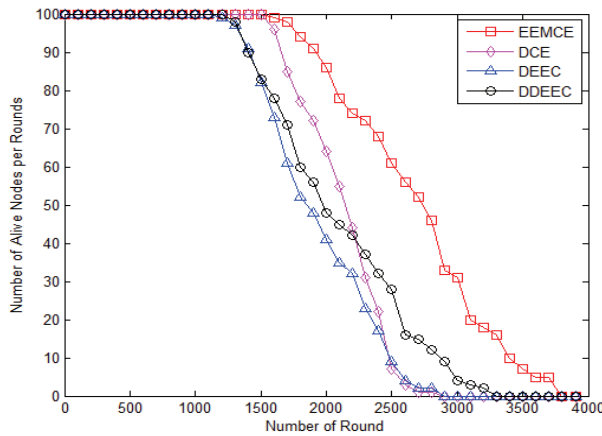
Fig. 3. Relationship between the running round of algorithms and the number of the alive node.
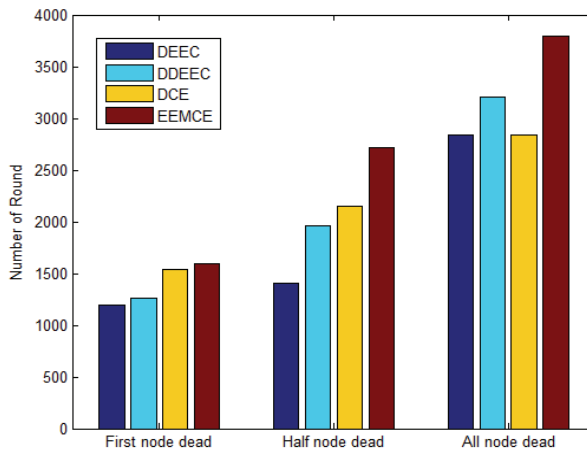

Fig. 4. The number of rounds for the first node dead, the half node dead and all nodes dead.

Fig. 5 reveals the number of packets received by the BS for different methods with the same energy. From the Fig. 5, it is suggested that the BS receives more packets for EEMCE method than the DCE, DEEC, and DDEEC at the same rounds. It is therefore revealed that the more data is transmitted in wireless sensor networks for EEMCE method than others.

The average energy consumption of each node in per round is shown in Fig. 6. From the following Fig. 6, it is suggested that the new algorithm (EEMCE) consumes less energy in each round, which down-regulates energy consumption by 20.5% per round compared with the DCE protocol. This shows that the new algorithm has better energy efficiency.

Fig. 7 shows the number round representing the first death node for different locations of BS. From Fig. 7, it is suggested that the number round corresponding to the first death node decreases with the variation of the location of BS far away from the center position of detection area. However, the number round representing the first death for EEMCE protocol remains larger than others at the same condition. This shows that the proposed method (EEMCE) exhibits longer stability period and better scalability than others.
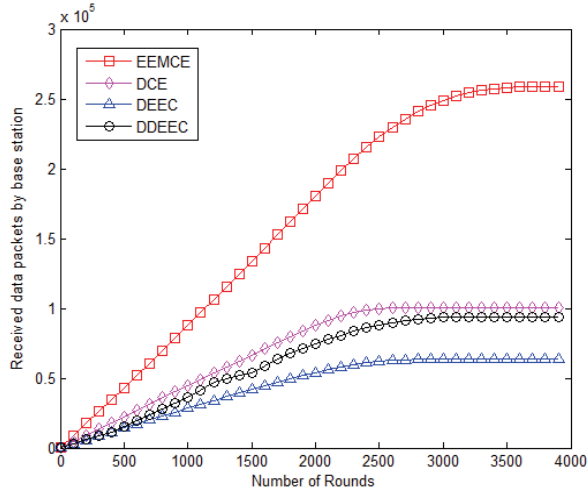
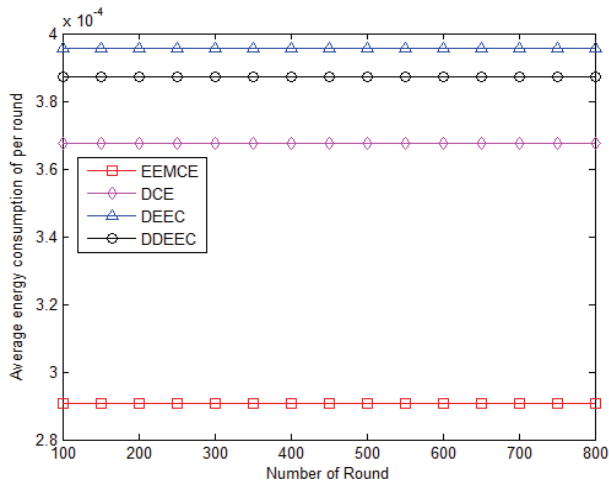**Fig. 5.** Number of received data packets by BS.

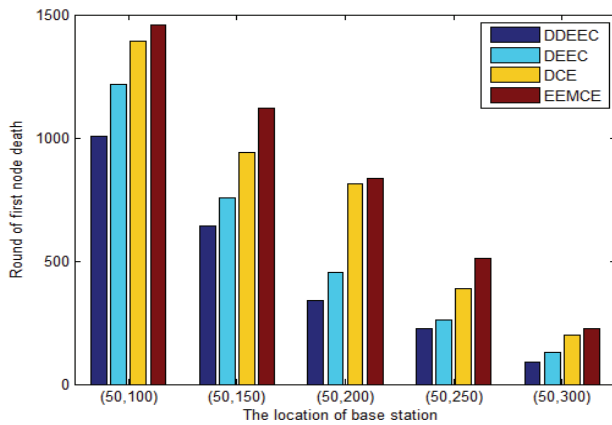**Fig. 6.** The energy consumption per round during steady period.

Fig. 7. The round number of the first death node for different locations of BS.

6. Conclusion

In the present paper, a novel CH election method that is based on the double-stage cluster-head election protocol is proposed. Firstly, the distance of between nodes and BS is used to lower the probability that nodes far away from BS become tentative CHs. Secondly, the energy and distance between tentative CH and nodes in the same cluster are exploited to select the final CH to avoid it locating at edge of cluster. Lastly, multi-hop is used for the CHs far away from the BS. The proposed method exhibits better performance in energy efficiency, stability period and scalability than other methods.

Acknowledgement

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