Journal of Computers Vol. 28, No. 4, 2017, pp. 227-235
doi:10.3966/199115592017082804024

Study on Energy-Saving Routing Algorithm Based on Wireless Sensor Network

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Received 18 October 2016; Revised 13 June 2017; Accepted 26 June 2017

Abstract. The biggest problem for the development of wireless sensor network is the limited energy of sensor. It has always been the research focus of routing protocol on wireless sensor network to effectively reduce node energy consumption, to balance energy consumption of the entire network, and to extend the life cycle of sensor network. By directing at problems of LEACH protocol such as uneven distribution of cluster heads, unreasonable cluster head selection and rotation mechanism, and single-hop communication of cluster heads with base station, this paper proposes an improved algorithm LEACH-DT (LEACH- Dynamic threshold) of LEACH protocol. In the first round of this algorithm, the base station will calculate the optimal number of cluster heads and select cluster head nodes according to node energy and node density. When the energy of cluster head is smaller than the energy threshold, rotation of cluster head nodes will be conducted, and data of cluster head will be transferred to the base station in a multi-hop way through the shortest path tree. According to the simulation experiment, the improved LEACH-DT algorithm has balanced energy consumption of various nodes in network, reduced average energy consumption of the nodes, postponed death time of the first node in network, extended the life time of network, and increased the network throughput.

Keywords: energy threshold, LEACH protocol, multi-hop, wireless sensor network

1 Introduction

With the rapid development of wireless communication technique, embedded technology, distributed management technology and microelectronics manufacturing technology, various intelligent hardware products have greatly changed our life. They have formed a huge industry chain, and possess important social value and economic value. All these have promoted the development of wireless sensor network researches. WSN (Wireless Sensor Networks) is a network system with self-organization nature. It is mainly formed by placing a large number of sensor nodes with wireless communication function in the area waiting for monitoring. Data acquired by nodes in the network will be transferred to the base station through the network formed via self-organization of nodes, and then the base station will transfer the data to users by utilizing the existing networks. This is a brand-new information acquisition system [1].

Wireless sensor network node is restricted to conditions in the aspects of volume and cost, so the quantity is small and energy supplement is difficult. Therefore, energy conservation issue has always been the important topic of wireless sensor network researches. The purpose of our work is to minimize the energy loss of wireless sensor networks. Energy conservation can be realized from two aspects which

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are information acquisition and processing as well as data transmission. At present, integrated circuit has already reached the grade of 22 nanometers, and the improvement space for power dissipation of information acquisition and processing is small. However, routing protocol still has a huge research space. That's why we chose energy-efficient routing algorithms as our research. Routing protocol can be divided into planar routing protocol and hierarchical routing protocol according to the topological structure. Planar routing protocol requires maintenance for a large amount of routing table information in the working process. It lacks optimal management for communication resources; the self-organization synergetic algorithm is complicated; the routing hop count is high; the response to changes of network topology is slow. As a result, it cannot adapt to the development of large-scale wireless sensor network. Hierarchical routing protocol can reduce the data size transferred in the network through cluster head collection and data fusion, so these problems are solved well [2].

LEACH protocol [3] (Low Energy Adaptive Clustering Hierarchy, LEACH) is the earliest hierarchical routing protocol in wireless sensor network, and there are many improved versions on the basis of LEACH protocol, such as LEACH-C protocol, TEEN protocol and UCR protocol. LEACH-C protocol [4] is a centralized control hierarchical routing protocol proposed by Heinzelman, Chandrakasan and Balakrishnan. As for its main improvements, cluster head selection is conducted via centralized control of base station; the surplus energy of nodes is considered in the process of cluster head selection; the probability of treating low-energy nodes as cluster heads is reduced. TEEN protocol reduces the data transmission quantity by adopting the method of data filtering, and decides whether the nodes can send data through two parameters which are hard threshold and soft threshold. Hard threshold is used to restrict the absolute value of data monitored, and soft threshold is used to restrict the absolute value of changing amplitude of data monitored [5]. As a routing protocol of uneven clustering based on distance, UCR (Unequal Clustering Routing) protocol selects cluster heads according to the surplus energy of cluster head nodes [6]. UCR protocol has solved the problem of fast energy consumption of cluster heads near the base station area, and adopts uneven competition mechanism. Through this method, clusters with different areas are formed: clusters near the base station have a smaller area, while clusters far away from the base station have a larger area. As a result, cluster heads near the base station can retain more energy to transmit data of other clusters. LEACH-SM [7] (LEACH-Spare Management) protocol based on redundant node management obtains redundant nodes in the network by calculating the coverage rate. When redundant nodes are treated as spare nodes, transmission of redundant data is reduced. LEACH-M [8] (cluster head multi-hop algorithm based on LEACH protocol) protocol will form a multi-hop optimal path leading to the base station among cluster heads. In this way, energy consumption of cluster head nodes is reduced and the network lifetime is extended. Based on analysis and comparison of these improved algorithms, by combining with characteristics of LEACH protocol, this paper designs an improved algorithm of dynamic threshold based on LEACH protocol (LEACH-DT).

This paper is divided into five chapters. The introduction section introduces the status and motivation of this work. The second part analysis LEACH protocol. The third chapter designs an improved algorithm of dynamic threshold based on LEACH protocol (LEACH-DT). The forth chapter is the algorithm simulation and performance analysis of LEACH-DT. The last chapter is conclusions.

2 LEACH Protocol Analysis

2.1 Introduction of LEACH Protocol

LEACH algorithm is composed of two different stages. The first stage is cluster establishment stage comprising cluster head selection and cluster formation. The second stage is stable working stage, including data acquisition, fusion and sending to the base station. LEACH protocol adopts cycle operation mechanism, and each cycle is called a round.

The specific implementation method of cluster head selection algorithm of LEACH protocol is as follows. After the new round is started, all nodes will generate a number between 0 and 1 at random, and meanwhile a threshold T(n) will be generated in this round. If the random number generated by the node is smaller than the threshold T(n), this mode will be selected as cluster head node of this round.

The expression of threshold T(n) is as follows:

$$\mathrm{T}(n)=\begin{cases}\dfrac{p}{1-p[r mod(1/p)]} & (n\in G)\\ 0 & (others)\end{cases}. \quad \textbf{(1)}$$

In the above formula, p means the expected value about the percentage of cluster head nodes in all nodes; r refers to the value of subtracting 1 from the current number of rounds; G represents the set of nodes never selected as cluster heads in the previous 1/p rounds.

As for the cluster head node, the news of being selected as cluster head will be reported in the whole network. Other nodes will select the one with the strongest signal as cluster head according to the signal strength. Moreover, they will issue information to the cluster head, and join the cluster. When the cluster is established, the cluster head node will create and issue TDMA time slot table to member nodes, and allocate corresponding time slot to every node. At stable stage, member nodes will turn off the transceiver beyond the time slot allocated to them, so as to save energy. They will send data to the cluster head only when the time slot allocated to them arrives. The cluster head will integrate all data from member nodes, and then send them to the base station.

2.2 Defects of LEACH Protocol

Clustering algorithm and cluster head rotation mode of LEACH protocol have guaranteed that all nodes in the network can become cluster head node at equal probability. By transferring data information among various nodes via MAC mechanism of TDMA, it has avoided conflict of communication inside the cluster and between clusters, and extended the network lifetime. However, LEACH protocol still has the following defects:

(1) LEACH protocol does not consider the influences of surplus energy, density and geographic position of nodes when selecting cluster head. Nodes with little surplus energy and other nodes can be selected as cluster head at equal probability, which will accelerate the death rate of these nodes.

(2) LEACH ignores the distance from cluster head to the base station, and transfers data to the base station in a single-hop way. When the distance between these two is long, very huge energy consumption will be caused.

(3) Cluster head distribution in LEACH routing protocol algorithm is random. Cluster heads in some regions might be denser, which will cause the imbalance of network clustering and increase the loss of communication capability in the cluster.

(4) After complete data transmission of every round in LEACH routing protocol algorithm, cluster heads of the whole network should be selected again, regardless of the energy left in the cluster head. Unnecessary cluster head selection will cause energy waste.

(5) After selection of each round is over in LEACH protocol, time slot should be allocated to member nodes in the cluster. Allocation of time slot can realize the effect of energy conservation by utilizing dormancy, but allocation of time slot will cause energy consumption of cluster head.

3 Algorithm Improvement of LEACH Protocol

3.1 Cluster Head Selection

This algorithm completes things consuming a large amount of energy including cluster head selection and communication route establishment between cluster heads in wireless sensor network by utilizing the advantages of base station such as sufficient energy and strong calculation ability, so as to reduce energy consumption of sensor nodes and extend survival time of the entire network [9]. Cluster head selection is divided into whole-net cluster head selection and cluster head rotation within the cluster. The work of whole-net cluster head selection is completed by the base station, and cluster head rotation within the cluster is completed by the cluster head. In the network, whole-net cluster head selection will be conducted at first. Each node will report its energy, number of neighbor nodes and node address to the base station, and the base station will work out the optimal number of cluster heads according to formula (2) [10].

$$\mathrm{K} = \frac{M}{2} \times \sqrt{\frac{N\varepsilon_{fs}}{\pi(\varepsilon_{amp}d^4 - E_{elec})}}. \tag{2}$$

In formula (2), N means the number of nodes in the network; E_{elec} represents the energy of receiving circuit; d refers to the expectation about the square of multi-hop communication distance between cluster head and base station; M2 indicates the area of node region. Then the base station will work out K cluster head nodes via greedy algorithm according to node energy and number of neighbor nodes. Neighbor node refers to the node within the scope of radius R from the node, and every node has different neighbor nodes; the radius $R = \sqrt{M^2/K\pi}$. The base station will issue K cluster heads and cluster ID to the whole network, and cluster head nodes will receive their selection information.

3.2 Cluster Head Transfer

After a round is over in LEACH protocol, whole-net cluster head selection will be conducted. No accurate estimation is conducted for the surplus energy of cluster head. If the surplus energy is enough to transfer data, it is not necessary to change the cluster head [11]. In this algorithm, we try to reduce energy waste caused by cluster head rotation and cluster head selection through dynamic energy threshold. A routing algorithm of dynamic threshold based on base station control (LEACH-DT) is designed. In this algorithm, the cluster head node will calculate the average energy Eaverage of nodes in the cluster according to the energy information from cluster member nodes, as shown in formula (3):

$$E_{average} = \sum E_i / N. \tag{3}$$

In the formula, the symbol Ei means the surplus energy of node i; N refers to the total number of existing nodes in the cluster. The energy threshold Eth is set as a half of the average value of surplus node energy in the cluster, as shown in formula (4):

$$E_{th} = 0.5 \times E_{average}. \tag{4}$$

When the value of cluster head energy is smaller than the threshold, cluster head rotation within the cluster should be conducted. The process of cluster head rotation is as follows. Firstly, the cluster head will calculate the position of centroid (Xc, Yc) in the cluster, and formula (5) and formula (6) are the calculation formulas:

$$X_c = \sum_{i=1}^{n} X_i / N. \tag{5}$$

$$Y_c = \sum_{i=1}^{n} Y_i / N. \tag{6}$$

(X_i, Y_i) is the coordinate of node i; N refers to the number of existing nodes in the cluster. The distance D(i) between existing node i in the cluster and centroid (Xc, Yc) is calculated, as shown in formula (7):

$$\mathrm{D}(i) = \sqrt{(X_c - X_i)^2 + (Y_c - Y_i)^2}. \tag{7}$$

Nodes whose surplus energy is greater than the average energy of nodes within the cluster will form the candidate set, and node with the smallest D(i) value is selected as the next cluster head. Energy consumption of communication within the cluster can be reduced by making the cluster head located in a region with high relative density of nodes close to the geometrical center.

In order to solve the problem of allocating time slot to member nodes in the cluster during each round of selection, this scheme adopts the strategy of making cluster head node and candidate node exchange the time slot. When the cluster head is exchanged with the candidate cluster head node, the cluster head node can treat the time slot of candidate cluster head node as its time slot.

3.3 Communication between Clusters

According to literature [12], we can know that when the communication distance between nodes is greater than the critical value, transmission loss is in direct proportion to the fourth power of distance.

Therefore, in order to save energy, we must reduce long-distance communication. This scheme transfers data to the base station by adopting multi-hop routing in communication between clusters.

Mature shortest path algorithms under wired environment include Dijkstra algorithm, SPFA algorithm, Bellman-Ford algorithm and so on [13]. By combining with characteristics of base station control, this paper decides to adopt Dijkstra algorithm. As for the main feature of Dijkstra algorithm, it extends outward layer by layer by centering on the initial point till reaching all nodes. The strategy of greedy algorithm is adopted. Theoretically speaking, all nodes can be directly connected to the base station via electromagnetic wave, and such communication distance is the shortest. If shortest path algorithm under wired environment is still used, we suppose that when communication distance between two cluster heads is greater than the value 3 times the perception radius R, the two nodes are inaccessible. Under such situation, the base station uses Dijkstra algorithm to gain the shortest path tree of the entire network. In the shortest path tree, we conduct data forwarding via cluster number, and the base station will issue the shortest path route with the broadcasting of cluster head. Each cluster head will store a simple routing table including numbers of the previous cluster and next cluster. The shortest path tree adopts cluster number rather than cluster head number, so this routing table will remain effective even if the cluster head is changed.

3.4 Data Fusion

Data fusion can reduce unnecessary data transmission by eliminating redundant data, thus consumption of node energy will be reduced [14]. We have slightly changed the method in TEEN protocol, and set soft threshold only. When the absolute value of the difference between data detected by the node and the observed value is smaller than the soft threshold, the node will only send data packets with node address and surplus node energy. In this way, data can be issued to cluster head node. When the absolute value of the difference between data detected by the node and the observed value is greater than the soft threshold, the detected data will be added into the data packet.

3.5 Improved Algorithm LEACH-DT Based on LEACH

By analyzing and improving the problems in four aspects covering cluster head selection, cluster head transfer, communication between clusters and data fusion in LEACH protocol in the above four sections, this paper has gained the workflow of LEACH-DT algorithm:

(1) Each node acquires its position information, surplus energy and number of neighbor nodes, and reports the above information to the base station node. Base station node works out the optimal number of cluster heads K, and obtains cluster head nodes and shortest routing table between clusters. Moreover, it will broadcast such information throughout the network.

(2) The cluster head broadcasts the information of being selected as cluster head within the radius of d0, and other nodes join corresponding cluster head according to the distance. The cluster head allocates time slot, and broadcasts the time slot in the cluster. Common nodes receive their time slot allocation, and enter dormancy.

(3) Member nodes acquire data. They will package data acquired, node position and surplus energy into a data packet, and transfer it to the cluster head node.

(4) The cluster head node conducts data fusion for data packet received from the cluster, and the data packet will be sent to the base station in a multi-hop way through cluster-level routing.

(5) The cluster head node calculates the threshold of node energy within the cluster, and makes a comparison between its surplus energy and dynamic energy threshold. If the energy of cluster head is greater than the energy threshold, please return to step (3) directly. If its energy is smaller than the energy threshold, the cluster head will work out cluster head node of the next round according to energy of nodes in the cluster as well as the distance to centroid. Moreover, it will exchange cluster information and time slot with the next cluster head node at the next data interaction. Return to step (3).

4 Algorithm Simulation and Performance Analysis

4.1 Setting of Simulation Environment

This paper uses NS-2 for simulation. Network scene design of simulation experiment is as follows. Nodes of wireless sensor network are distributed in a square region at random. All sensor nodes have the same function and form; each sensor node has a mark; every node has limited energy capacity of battery; the node position is fixed. Base station node of the sensor network is fixed. The data information transmission and receiving power of wireless sensor network nodes can be automatically adjusted according to the distance change between two nodes. In order to fully compare the adaptation situations of two protocols to the network, we have simulated situations of base station node inside and outside the coverage area respectively. Environmental parameters required by wireless sensor network are shown in Table 1.

Table 1. Experiment parameters

Parameter	Value
Network coverage area	(0, 0) – (200, 200) m
Position of base station node	(0, 0)
Total number of nodes	400
Initial energy of node	1J
Size of data packet	4000bit
Size of control information	200bit
Transmission / receiving circuit energy	50nJ/bit
Power amplification coefficient of multi-path attenuation model	10pJ/(bit•m2)
Power amplification coefficient of free-space model	0.0013pJ/(bit•m2)
Energy consumption of data fusion	5nJ/bit
Data fusion rate	0.7
Critical transmission distance	87m

4.2 Analysis on Simulation Results

This section compares LEACH protocol, LEACH-C protocol and LEACH-DT protocol via simulation according to environment setting in 3.1. Performance indexes considered in simulation at this time mainly include network lifetime, surplus energy of whole network and data size received by base station.

Network lifetime. Network lifetime is defined as the active working time when node survival rate is above 80%. As shown in Fig. 1, the death time of the first node in LEACH, LEACH-C and LEACH-DT is the 280th round, 430th round and 520th round respectively, and the network lifetime is 340 rounds, 450 rounds and 530 rounds. The network lifetime of LEACH-DT protocol is extended by 50% when compared with that of LEACH and lengthened by 20% when compared with that of LEACH-C. LEACH-DT protocol considers surplus energy of node and node density when selecting cluster head. In this way, it has avoided energy exhaustion and premature death caused by the situation in which node with low energy is selected as cluster head under random cluster head selection of LEACH protocol. LEACH-DT protocol is not like LEACH-C protocol that has to make all nodes transfer information to the base station at the beginning of each round, and to conduct clustering again. The strategy of cluster head rotation within the cluster adopted by LEACH-DT protocol has reduced unnecessary clustering and saved energy consumption. In LEACH-DT, cluster head transfers data to the base station in a multi-hop way by adopting shortest path tree, which has reduced long-distance transmission and saved energy. In LEACH protocol and LEACH-C protocol, distribution of cluster head nodes has randomness, and situation of concentrated cluster heads might happen. As a result, communication loss within the cluster will increase. In LEACH-DT protocol, base station node conducts clustering according to the density of nodes. Therefore, the clustering is even and communication loss within the cluster can be reduced. Its average energy consumption of nodes in each round is less than that of LEACH and LEACH-C.

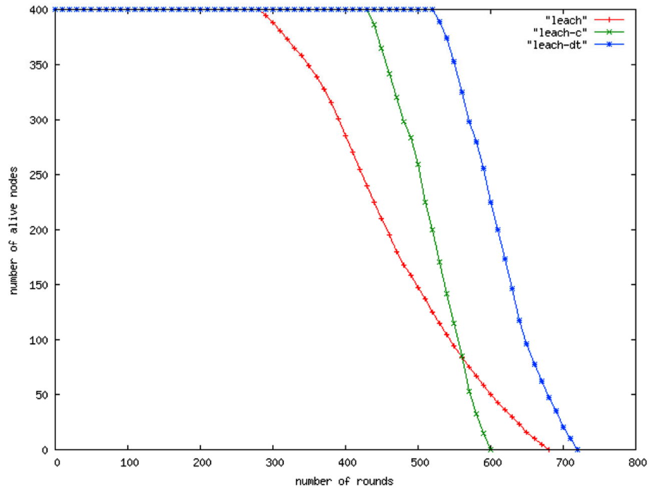

Fig. 1. Network lifetime of base station in node area

Surplus energy of whole network. Fig. 2 shows the changing situations about surplus energy of whole network of LEACH, LEACH-C and LEACH-DT with time. The three protocols have the same surplus energy of whole network under the original state. The energy curve of LEACH and LEACH-C is steep, showing that the energy consumption in unit round is huge. However, the corresponding curve of LEACH-DT protocol is gentle, showing that its energy consumption in unit round is smaller than that of the other two. With the increase of rounds, nodes far away from the base station in LEACH begin to die. As a result, the number of nodes decreases and energy is consumed. The death time of nodes in LEACH-C is later than that of LEACH. The ultimate energy exhaustion time is earlier than that of LEACH. In terms of the reason for the fast energy consumption of LEACH and LEACH-C, their cluster head distribution is uneven and energy loss of communication within the cluster is increased; the cluster head communicates with base station in a single-hop way, and energy consumption of cluster head is huge. LEACH-DT does not need to select cluster head in each round and the clustering is even. During cluster head rotation in the cluster, position and surplus energy of the candidate node will be considered at first. Moreover, the cluster head communicates with base station in a multi-hop way. Owing to these measures, energy consumption of the single round in LEACH-DT is low, and the surplus energy of whole network is higher than that of LEACH and LEACH-C.

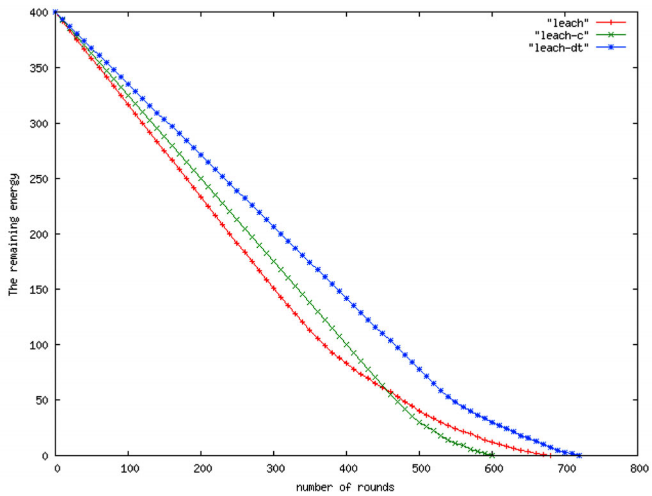

Fig. 2. Surplus energy of whole network of base station in node area

Data size received by base station. Network throughput is an important index of network protocol performance, and this paper measures network throughput by using data size received by base station. Fig. 3 shows the data size received by base station. According to Fig. 3, when no node dies in the same round, LEACH, LEACH-C and LEACH-DT protocols have the same data size received by base station. The node death time of LEACH-C is later than that of LEACH, but earlier than that of LEACH-DT. Therefore, data size received by base station in LEACH declines first, followed by LEACH-C and LEACH-DT. According to the comparison curve, data size received by base station in LEACH-DT protocol is improved by 40% when compared with that of LEACH protocol, and improved by 20% when compared with that of LEACH-C protocol.

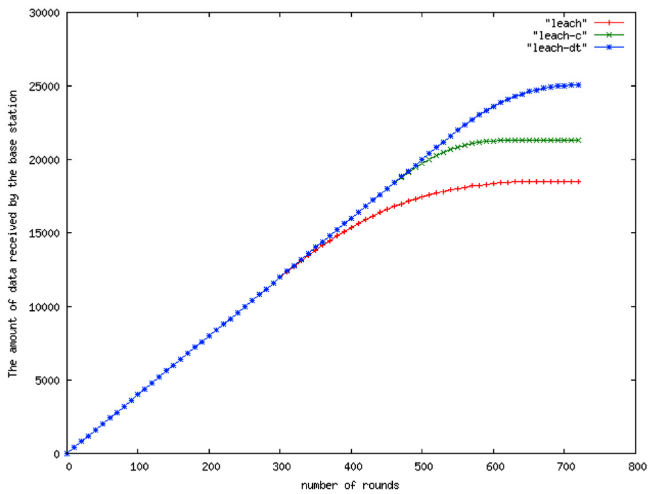

Fig. 3. Data size received by base station in node area

According to the simulation curves in three aspects covering network lifetime, surplus energy of whole network and data size received by base station, LEACH-DT protocol is better than LEACH protocol and LEACH-C protocol in all the three aspects. In LEACH-DT protocol, we conduct cluster head selection through base station control. Therefore, cluster head distribution is even and communication loss in the cluster is reduced. Whether to change the cluster head is decided according to the dynamic threshold in cluster, thus frequent cluster head rotation is avoided. Cluster head transfers data to the base station node in a multi-hop way via shortest path tree, thus loss caused by long-distance communication to cluster head node is reduced. Measures of these aspects are quite effective for the improvement of LEACH protocol.

5 Conclusions

Based on LEACH protocol study, this paper has designed a dynamic threshold clustering algorithm based on base station control (LEACH-DT). By fully utilizing the base station characteristic of abundant energy, this algorithm proposes improvement measures in four aspects such as covering cluster head selection, cluster head transfer, communication between clusters and data fusion. uses Then we build a network model and use NS-2 for simulation. According to the simulation experiment in fig.1, fig. 2 and fig. 3, the network lifetime of LEACH-DT is extended by 50% when compared with that of LEACH and lengthened by 20% when compared with that of LEACH-C, energy-consuming of the same data transmission LEACH-DT is lower than LEACH and LEACH-C, data size received by base station in LEACH-DT protocol is improved by 40% when compared with LEACH and improved by 20% when compared with LEACH-C. Therefore LEACH-DT can balance energy consumption of various nodes in the network, reduce the average energy consumption of nodes, postpone death time of the first node, extend life cycle of the network, and improve the network throughput.

This method still has some defects. Firstly, after cluster head rotation in the cluster, with the change of cluster head position, the original shortest path might not be the shortest path anymore, which will cause energy waste. Moreover, cluster head is not in the centroid position anymore. Secondly, multi-hop data transmission is adopted between clusters. As a result, cluster heads near the base station might run out of energy and die easily, for they have to transmit data of cluster heads far away from the base station.

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