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Research on Improved Low-Energy Adaptive Clustering Hierarchy Protocol in Wireless Sensor Networks

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Abstract: In wireless sensor networks (WSNs), due to the limited battery power of the sensor nodes, the communication energy consumption is the main factor to affect the lifetime of the networks. A reasonable design of the communication protocol can effectively reduce the energy consumption of the network system. Based on low-energy adaptive clustering hierarchy (LEACH), an improved LEACH protocol in WSNs is proposed. In order to optimize the cluster head (CH) election in the cluster setup phase, the improved LEACH takes into account a number of factors, including energy consumption of communication between nodes, remaining energy of the nodes, and the distance between nodes and base station (BS). In the steady phase, one-hop routing and multiple-hop routing are combined to transmit data between CHs to improve energy efficiency. The forward CH is selected as relay node according to the values of path cost. The simulation results show that the proposed algorithm performs better in balancing network energy consumption, and it can effectively improve the data transmission efficiency and prolong the network lifetime, as compared with LEACH, LEACH-C (LEACH-centralized) and NDAPSO-C (an adaptive clustering protocol based on improved particle swarm optimization) algorithms.
Key words: wireless sensor networks (WSNs), low-energy adaptive clustering hierarchy (LEACH), clustering, energy consumption, relay nodes
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0 Introduction

Wireless sensor networks (WSNs) composed of the nodes in form of self-organization according to the efficient routing protocol involve many low-cost nodes with limited battery energy, and have the functions of sensing, data processing and communicating. Nowadays, the size of microprocessor becomes smaller and its performance is more improved, which makes the WSNs widely used in various fields, such as battlefield detection, disaster management, weather monitoring, health monitoring, and health care services[1-2]. But in practical application, the wireless sensor nodes are randomly deployed, and most of them are deployed in the regions with harsh and inaccessible environments. Usually, sensor nodes can only rely on the energy of limited battery power. If some nodes run out of power, the life span and service quality of the network will be strongly reduced. Therefore, how to design a high-quality energy-efficient routing protocol becomes a hot issue in this research field.

WSNs can be divided into plane structure and hierarchical structure. There are lots of routing protocols put forward to improve the lifetime of networks, among which hierarchical algorithm is used frequently. The efficient topology-control structure based on appropriate hierarchical algorithm can effectively schedule and balance the consumption of the limited energy. The common hierarchical routing algorithms include low-energy adaptive clustering hierarchy (LEACH) protocol[3], hybrid energy-efficient distributed (HEED) clustering approach[4] and threshold-sensitive energy efficient sensor network (TEEN) protocol[5]. LEACH is the pioneer routing protocol proposed by Heinemann. The core idea of LEACH is randomly electing cluster head (CH) in a circular fashion, and assigning energy-intensive loads evenly to each node, so as to balance the energy consumption and prolong the network lifetime. However, due to the way of data transmission which involves direct communication between CHs and base station (BS), the position and energy of CHs are not taken into consideration. HEED algorithm combines transmission power control into clustering mechanism that forms single-hop cluster. In the cluster setup phase, communication energy consumption between the CHs is considered and the inter-cluster communication between

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the CHs is realized through the higher transmission power level. HEED algorithm performs a uniform distribution for the CHs. However, it does not consider the residual energy of the relay CHs in data transmission phase. TEEN protocol uses the multi-level clustering structure, and all the nodes are divided into multiple clusters. The nodes transmit their monitoring data to the CH, and the CH will send the data after fusion to a higher level CH until the data arrives at the BS. Based on this multi-level clustering structure, the TEEN protocol utilizes the hard and soft thresholds to provide the response-based applications. Since the hard threshold limits the transmission of observations which conform to the requirements of BS, the soft threshold further limits the transmission of data information when the perceived value does not change too much. Therefore, TEEN is not applicable to the applications which require periodic reporting of the data.

Based on LEACH, an improved LEACH clustering protocol in WSNs is proposed in this paper. The improved LEACH algorithm can solve the problems about unreasonable CH election and data transmission mode, and the imbalanced energy consumption. Compared with LEACH, LEACH-C (LEACH-centralized) and NDAPSO-C (an adaptive clustering protocol based on improved particle swarm optimization) algorithms, the proposed algorithm can better balance the network energy consumption, improve the data transmission efficiency and prolong the network lifetime.

1 Related Work

1.1 LEACH

LEACH structure diagram is shown in Fig. 1. Yellow circle represents the CH, and blue circle is on behalf of the member nodes within the cluster. LEACH protocol proposes the concept of “round”. A round is formed of two phases: cluster setup phase, and steady phase.

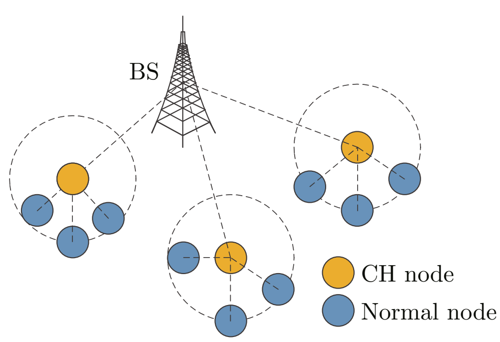

Fig. 1 LEACH structure model

In the cluster setup phase, every node has the chance to be chosen as a CH or not in the current round. This choice is made by using a random number between 0 and 1:

$$T(n)=\begin{cases}\dfrac{p}{1-p(r \bmod p^{-1})}, & n\in G\\ 0, & \text{else}\end{cases}, \tag{1}$$

where p represents the chosen percentage of CHs, r represents the current round, n represents a node, $T(n)$ represents the threshold value for choosing CH, and G represents the set of nodes which have not been chosen to be CH in the last p^{-1} rounds. The mod in Eq. (1) is modular arithmetic symbol. If the random number generated by the node is less than the above threshold $T(n)$, the node is selected as a CH for the current round. After the cluster setup phase, the CH will broadcast the message to the whole network to let the rest normal nodes join into the corresponding CH according to the received signal energy strength.

In the steady phase, members of the cluster send their data to the CH using time division multiple address (TDMA), and then the data will be sent to the BS after data fusion. LEACH protocol balances the network energy consumption and prolongs the network lifetime, but it still has the following shortcomings: ① the node’s current energy factor is not taken into account in the cluster setup phase; ② in data transmission phase, all CHs directly communicate with the BS by single-hop transmission mode, however the distance between the CH and the BS does not be considered; ③ CH is changed with the random rotation and the network constantly updates the cluster, which results in excessive energy consumption of the network.

1.2 Improved Algorithms Related to LEACH

LEACH-C[6] introduces a centralized control protocol in BS (or sink) to give the optimal number of the clusters to improve the original protocol. In the first stage, each node sends information about its location and current energy level to the BS. The BS calculates the average node energy, and let any node with energy below the average not become the CH of the current round. In order to minimize the sum of the squared distances between all non-cluster head nodes and the nearest CH, LEACH-C uses a simulated annealing algorithm to find the best clustering. The average energy of the network E_{avg} can be calculated by

$$E_{\text{avg}}=\frac{1}{N}\sum_{i=1}^{N}E_i, \tag{2}$$

where E_i is the current energy of the node i, and N denotes the number of sensor nodes. Compared with the BS in LEACH, the BS in LEACH-C determines the current CH in the CH election stage according to the node’s energy and position, and thus it is energy saving. However, LEACH-C relies heavily on nodes’ location. So each node requires global positioning system (GPS), which is expensive and consumes extra energy. These two algorithms focus on the optimization of CH and do not consider the energy consumption in the data transmission mode. According to their data transmission mode, the CH communicates directly with BS, without considering the current energy, location factors of the CH and the amount of data the CH can transmit. All these will be not conducive for wireless sensor nodes with limited energy to work efficiently. NDAPSO-C[7] introduces a clustering algorithm based on improved PSO and routing protocol between clusters. Fitness function contains the energy consumption of communication between nodes, the remaining energy of CHs, the distance between CHs and member nodes within the clusters, and the energy-consuming balance of nodes. Optimal CHs are selected by comparing the fitness values of particles. In addition, there are already lots of improved algorithms based on LEACH algorithm. LEACH-CE (LEACH-centralized efficient)[8] strives to solve the problems that some nodes with higher energy cannot be chosen as CHs, and CHs with less energy will die early in some rounds. Since the position information is not considered in the CH selection, it results in uneven energy consumption and increases intra communication cost. Tang et al.[9] proposed EHA-LEACH (energy harvested aware LEACH) algorithm. It emphasizes the improvement in clustering phase. Position measurement and energy consumption state of nodes should be taken into consideration. The energy potential function of the nodes is introduced to make the nodes with higher energy become CH. It performs better in terms of energy efficiency and network life than LEACH, but high cost and complexity are the main problems in this protocol. Jerbi et al.[10] proposed O-LEACH (orphan-LEACH) algorithm. Under the network model with high connectivity and high coverage, the algorithm solves the data transmission problem of the isolated nodes in the network. The member nodes in the cluster act as the gateway of the isolated nodes, and the gateway nodes aggregate the data and send it directly to the BS. Compared with LEACH, O-LEACH provides wider coverage and better connection rate. The main problem of this protocol is to find the information of the isolated nodes, and the data transmission delay and control of the costs are also the problems to be considered. Lee et al.[11] proposed DL-LEACH (dual-hop layered-LEACH) protocol. The algorithm supports the improvement in the transmission phase and the measurement of the distances from the low level nodes to the CHs and BS. If the distance from the nodes to the BS is less than the distance from the nodes to the CHs, the nodes send their data to the BS directly, otherwise the data is sent through the CHs from the remote node to the relay nodes, and then to the BS. Compared with LEACH, the protocol has greatly improved the energy consumption of the network, but it is not applicable to the large-scale networks.

2 Proposed Algorithm and Network Model

2.1 Improved Algorithm Description

The improved LEACH algorithm proposed in this paper takes distributed way to construct the path with the least energy cost from the data source node to the BS. The algorithm optimizes the CHs' election and data transmission mode to achieve the purpose of prolonging the network lifetime and improving the efficient data transmission. At the initial phase of the network, BS sends the initialization message with the power broadcast covering the whole network. After receiving the signal, the sensor node estimates the distance from itself to BS, and then the sensor node broadcasts the neighbor discovery message in the communication radius with the preset transmission power. When the sensor nodes receive the neighbor nodes' discovery message (including the node ID and energy information) according to the strength of the received message to estimate their own distance with the neighboring nodes, they establish the adjacent nodes' information table. In the cluster setup phase, the nodes in the BS hop range communicate directly with the BS, and the nodes outside the BS hop range participate in the CH election. The CH is selected according to the threshold formula and the established neighbor information table. The nodes in the CH communication range selectively join a CH according to the data transmission energy consumption and build the neighbor information table. The normal nodes that do not join any CH will communicate directly with the BS. In the steady phase, the improved algorithm uses the neighbor information table to select CHs from the forward CH nodes as the relay node.

2.2 System Model

Sensor Network Model The improved algorithm has the same network model as LEACH and LEACH-C algorithms: ① the sensor nodes are randomly distributed in a square large detection area (the BS is deployed out of the detection area periphery and it is unique); ② the position of sensor nodes and the BS are unchanged after deployment; ③ the initial energy of sensor node is the same, and at any time, residual energy of the node is known, but the BS's energy is not restricted.

In the above network model, we give the definition of neighbor nodes, forward neighbor nodes and forward cluster head nodes in the network. Some definitions are listed as follows based on the above model.

Definition 1 The neighbor node set of the node i is defined as

$$N(i) = \{j | j \in V, d(i,j) < R\}, \tag{3}$$

where V is the set of all sensors, $d(i,j)$ represents the distance between the nodes i and j, and R is the node communication radius.

Definition 2 The forward neighbor node set of the node i is defined as

$$\mathrm{FN}(i) = \{j|j \in N(i), d(j, \mathrm{BS}) < d(i, \mathrm{BS})\}, \quad (4)$$

where $d(i, \mathrm{BS})$ is the distance from the node i to BS.

Definition 3 The forward cluster head node set of the cluster head i (CH_i) is defined as

$$\mathrm{CN}(i) = \{j|j \in \mathrm{FN}(i), d(\mathrm{CH}_j, \mathrm{BS}) < d(\mathrm{CH}_i, \mathrm{BS})\}, \quad (5)$$

where $d(\mathrm{CH}_i, \mathrm{BS})$ is the distance from CH_i to BS.

Network Energy Consumption Model The energy consumption of the sensor nodes mainly includes three parts: perceived energy consumption, communication energy consumption, and data processing energy consumption, among which the communication energy consumption is the main part. If the node sends l bit data to another and the distance between them is d, the energy consumption of the node is

$$E_{\mathrm{Tx}}(l, d) = lE_{\mathrm{e}} + l\varepsilon_{\mathrm{a}} d^{\alpha}, \quad (6)$$

where E_{e} is the energy consumption of the transmitter and receiver circuits, ε_{a} is the energy consumption of the power amplifier, and α is the path loss index. There is

$$\alpha = \begin{cases} 2, & d < d_0 \\ 4, & d \geqslant d_0 \end{cases}, \quad d_0 = \sqrt{\frac{\varepsilon_{\mathrm{fs}}}{\varepsilon_{\mathrm{mp}}}}, \quad (7)$$

where, d_0 is the distance threshold; $\varepsilon_{\mathrm{fs}}$ and $\varepsilon_{\mathrm{mp}}$ are the energy dissipation coefficients of the power amplifier circuit in different communication modes. The energy consumption for receiving l bit data can be expressed as $E_{\mathrm{Rx}}(l) = lE_{\mathrm{e}}$.

3 Implementation of the Improved Algorithm

The improved LEACH algorithm aims at prolonging the network lifetime and improving the efficient data transmission by optimizing the CHs' election, clusters' formation and data transmission mode. In the CHs' election, the node within the BS communication range directly communicates with the BS, and the node outside the BS communication range participates in the CH election. A node is selected as CH according to the established neighbor information table which contains the node's ID and current energy. The remaining normal nodes choose the best CH to join according to the distance relationship between them. The normal node that does not join any CH will communicate directly with the BS. In the data transmission phase, each CH selects the best CH from its forward CH nodes' set as its relay node until the data is transmitted to the BS communication range. The details of the proposed energy efficient protocol are as follows.

Optimizing the CHs' Election Considering the randomness of LEACH and LEACH-C and the importance of CH selection, this paper synthesizes the node position and energy information to improve the threshold formula[12]:

$$T(n) = \begin{cases} \dfrac{p}{1 - p(r \bmod p^{-1})} \dfrac{E_i}{E_{\mathrm{avg}}} \times \\ \quad \dfrac{d(i, \mathrm{BS})}{d_{\max}(i, \mathrm{BS}) - d_{\min}(i, \mathrm{BS})}, & n \in G \\ 0, & \text{else} \end{cases}, \quad (8)$$

where $d_{\max}(i, \mathrm{BS})$ and $d_{\min}(i, \mathrm{BS})$ represent the maximum and minimum distances from the node i to the BS, respectively. As the node energy changes with the operation of the network, this paper introduces the ratio of current energy to network average energy into the threshold formula. Thus, the cluster selection is the relationship between the nodes and the overall energy level of the network, so as to balance the overall energy consumption of the network. Besides, it considers the position relationship between the joined node and the BS, and optimizes the CH election from two aspects.

Optimizing the Mode of Nodes Joining into the Cluster After the multiple-hop forwarding path of the backbone transmission network composed of CHs is generated, the CH broadcasts the information including its own ID and transmits data to the whole network. The existing clustering algorithm takes the shortest distance standard of the sensor node and accepts the signal intensity standard without taking the difference in the amount of transmission data into account and realizing the load balance of the CH.

Definition 4 Considering the distance between nodes and the energy consumption of data transmission, factor of nodes joining into CH is described as

$$\mathrm{Ep}(i, \mathrm{CH}) = \frac{d(i, \mathrm{CH})}{d_{\mathrm{avg}}} \quad (9)$$

$$\left.\begin{aligned} d_{\mathrm{avg}} &= \frac{1}{k}\sum_{i=1}^{k} d(i, \mathrm{CH}) \\ d(i, \mathrm{CH}) &\leqslant R \end{aligned}\right\}, \quad (10)$$

where k is the number of the sensor nodes, $d(i, \mathrm{CH})$ represents the distance from the sensor node i to CH, and d_{avg} is the average distance from the node within R to the CH. Equation (9) can ensure clusters' load balancing.

Optimizing the Data Transmission Mode In the data transmission phase, LEACH and LEACH-C do not consider the actual position of the CHs. The thing that CHs communicate with the BS directly can lead to some of the CHs to be exhausted. The improved algorithm uses the neighbor information table to select CHs from the forward CH nodes. The forward CH is selected as the relay node according to the energy consumption of data transmission between CHs[13].

Definition 5 Energy consumption is determined primarily by the distance $d(\mathrm{CH}_i, \mathrm{CH}_j)$ between CH_i and CH_j and the amount of data. If CH_i sends l bit data to CH_j, factor of CHs to be relay nodes is described as

$$\varphi(i,j) = \frac{E_j}{E_{\mathrm{avg}}}\left(1 - \frac{d(\mathrm{CH}_i, \mathrm{CH}_j)}{R}\right). \quad (11)$$

It can be seen that the bigger the value of φ is, the greater the probability that CH_j becomes the relay node of CH_i will be.

The flow chart of improved algorithm is shown in Fig. 2, where τ is a random number generated by the node i.

As shown in Fig. 3, in the data transmission phase, if CH_1 needs to send the fused data to the BS, the process can be expressed in the following steps.

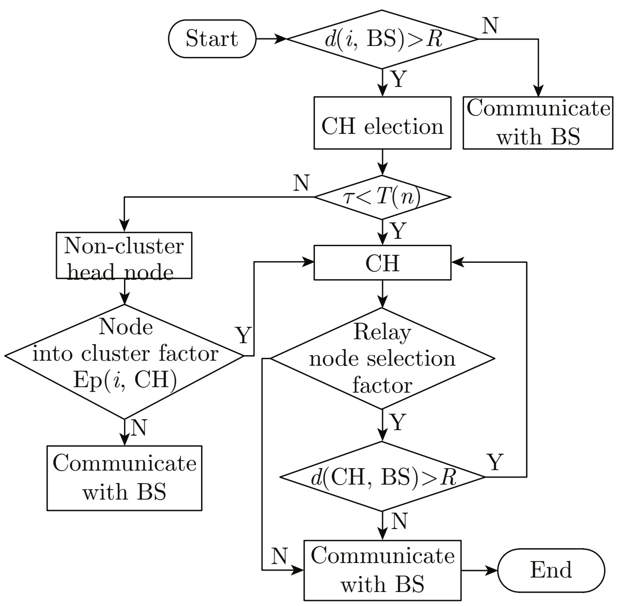

Fig. 2 The flow chart of improved algorithm

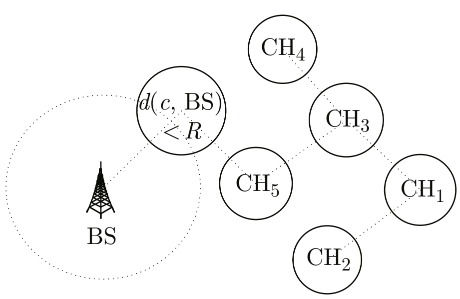

Fig. 3 The improved data transmission model

Step 1 CH_1 obtains its forward neighbor cluster node set $\{\mathrm{CH}_2, \mathrm{CH}_3, \cdots\}$ according to the neighbor information table.

Step 2 A CH with the lowest energy consumption of data transmission is selected as its relay node. If CH_3 satisfies the condition, CH_1 will transmit the data to CH_3.

Step 3 CH_3 selects its relay node according to Steps 1 and 2 until the last data is transferred to the node within the BS communication radius.

4 Simulation and Analysis

4.1 Parameters' Setting

In this paper, the proposed algorithm, LEACH, LEACH-C and NDAPSO-C are simulated under Matlab platform[14]. The simulation environment is to deploy 100 sensor nodes randomly in a square area of 100 m×100 m. The specific parameters are shown in Table 1. The random deployment diagram for the nodes is shown in Fig. 4.

Table 1 Simulation parameters

Parameter	Value
Network area	100 m × 100 m
Number of nodes	100
BS location	(50, 50)
Initial energy	0.5 J
Packet size	4 000
E_{e}	50 nJ/bit
$\varepsilon_{\mathrm{fs}}$	10 pJ/(bit · m^2)
$\varepsilon_{\mathrm{mp}}$	1.3 fJ/(bit · m^2)

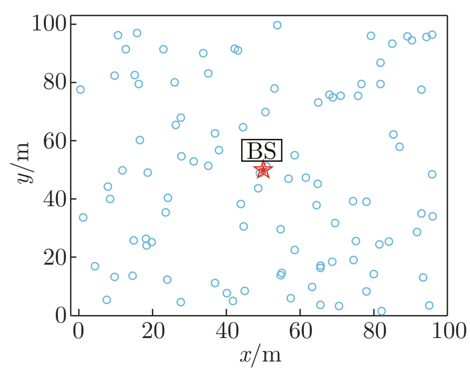

Fig. 4 Random deployment diagram

4.2 Performance Analysis

Network Lifetime Based on the energy consumption, the proposed algorithm takes the way of data transmission and the way of CH election into account, as compared with LEACH, LEACH-C and NDAPSO-C algorithms. The simulation results are shown in Fig. 5. It can be illustrated from Fig. 5 that the death time of the first node of the proposed algorithm is much later than that of other three algorithms. When the nodes in LEACH, LEACH-C and NDAPSO-C are all died, the number of dead nodes of the proposed algorithm is less than the half. Therefore, the improved algorithm achieves the goal of prolonging the lifetime of the network.

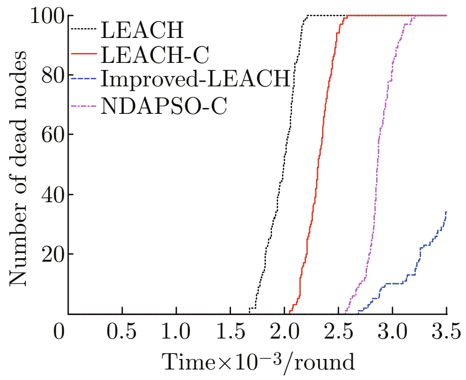

Fig. 5 Number of dead nodes for four algorithms

Average Residual Energy of the Network Because the energy of each node is limited, the network quality of service may be declined due to the depletion of some nodes[15]. Therefore, well balancing the energy consumption of each node to prolong the network lifetime and improve the quality of service is a key indicator index. In this paper, we take the energy, position of nodes and the energy consumption of data transmission into account. LEACH, LEACH-C, NDAPSO-C and the proposed algorithms are simulated and analyzed on the average energy consumption of network nodes, as shown in Figs. 6 and 7.

As shown in Fig. 6, in the same simulation environment, the average residual energy of the nodes in the proposed method is higher than that of LEACH, LEACH-C and NDAPSO-C respectively during the network operation. Figure 7 shows the similar trend of mean square error (MSR) of the residual energy with 10 times simulation for four algorithms within 2 000

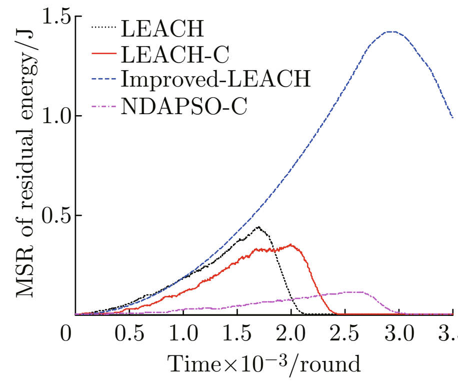

Fig. 7 MSR of the nodes' residual energy with 10 times simulation

rounds. With the network running, the time and variance of creating wave of the proposed method are much higher than those of other three algorithms. It indicates that the proposed algorithm has a significant effect on the balance of the whole network energy. The reason is that it uses the neighboring CH node as the relay node in the data transmission, and chooses the best path of the data transmission to reduce the uneven energy consumption of the node caused by the data transmission.

The size of the data transmitted by the network is often able to reflect the performance of the network system. In this paper, the data transmission relay node is introduced by the hybrid transmission[16], so that the number of data received by the BS is better, and the simulated result is shown in Fig. 8. It can be illustrated that the difference between LEACH and LEACH-C on data transmission volume is not obvious. Data transmission volume of NDAPSO-C is slightly higher than those of LEACH and LEACH-C. The number of data received by the proposed algorithm is much higher than those of other three methods. It is indicated form the figure that the number for the proposed method is 26.95 times higher than that for LEACH, 7.66 times higher than that for LEACH-C and 2.57 times higher than that for NDAPSO-C. Since the proposed algorithm

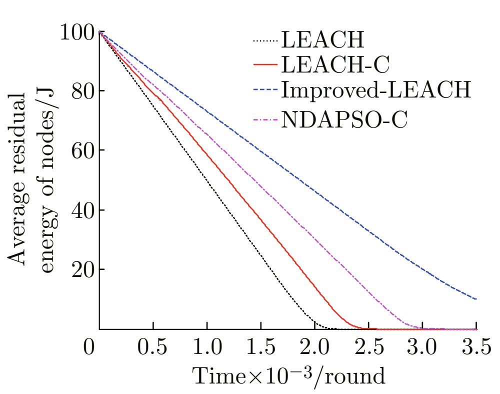

Fig. 6 The average residual energy for four algorithms

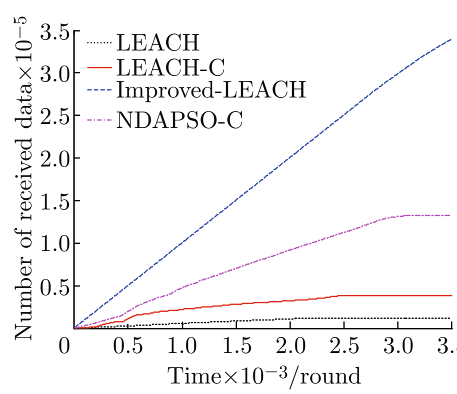

Fig. 8 Number of data received by the BS

introduces the relay node in the data transmission mode. The proposed method takes into account the energy consumption, the distance between CHs and the neighboring CHs, and selects the adjacent CHs as the relay node, so that the network survival time is extended and the BS receives more perceptual data. The relevant results in the above figure are shown in Table 2.

Table 2 Simulation data

Algorithm	Round for node death percentages			MSR of residual energy/J	Number of data transmitted
	1%	10%	100%		
LEACH	1 720	1 811	2 243	0.464 3	12 215
LEACH-C	2 030	2 158	2 606	0.443 4	39 408
NDAPSO-C	2 580	2 730	3 156	0.139 3	132 680
Improved-LEACH	2 630	3 155	4 958	1.441 2	341 422

5 Conclusion

The proposed algorithm has mainly improved in two aspects based on the analysis of LEACH protocol. In the cluster setup phase, it considers the node's energy level and position to optimize the threshold formula, which makes the CHs' election more reasonable. In the steady phase, it defines the relay selection factor based on the analysis of energy consumption on data transmission between nodes, which makes the data transmit in the energy efficient path. In summary, the proposed scheme has achieved a goal of prolonging the lifetime of sensor networks, as compared with LEACH, LEACH-C and NDAPSO-C respectively. The next work can use the mobile network nodes to optimize the data transmission topology, prolong the network lifetime and improve the network service quality even better.

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