Optimal Number of Cluster Heads for Selection Cooperation in Clustering Wireless Sensor Networks

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Abstract. In clustering wireless sensor networks, the number of cluster heads has great impact on energy consumption and transmission reliability of the system. With the increase of the number of transmission rounds, the area where the survival nodes are located gradually shrinks. In order to reduce the energy consumption of sensor nodes and improve the network lifetime, this paper proposes a dynamic cluster head (CH) number optimization scheme for selection cooperation. In order to reflect the area where the survival node is located, the network area as a variable is introduced into the energy consumption model. According to the behavioural characteristics of various nodes in the two-stage selection cooperation, the energy consumption model for each round is established. By solving the energy consumption model, the optimal number of cluster head in each round can be obtained. In this way, each round of transmission is carried out according to the minimum energy consumption. The simulation results show that the proposed scheme can reduce the energy consumption of the network, avoid energy waste caused by improper selection of cluster heads and extend the network lifetime.

1. Introduction
Wireless sensor networks (WSNs) have attracted more and more attention and are widely used in various fields, such as smart grid, environmental monitoring and agricultural production [1-3]. A wireless sensor network consists of a lot of tiny and energy-limited nodes. When one of the nodes runs out of energy, data acquisition and transmission will be interrupted, affecting network performance. In order to reduce energy consumption and maximize the network lifetime, a Low-Energy-Adaptive Clustering Hierarchy (LEACH) was proposed [4]. It was a typical clustering protocol and selected cluster head (CH) randomly in a round-robin manner. In this way, the energy consumed by the entire network was evenly distributed to each node, thereby reducing energy consumption and increasing the network lifetime. However, the random selection of cluster heads also brings some disadvantages. Cluster heads (CHs) may be more densely distributed, resulting in more interaction overhead and energy consumption. CHs may also be sparsely distributed, which will make the distance between some nodes and the CH too far, so that the collected data by the nodes cannot be reliably transmitted to the CH. Some CHs are located at the edge of the network, which makes their member node consume more energy to send data to them.

To overcome these shortcomings, several improved clustering schemes with different CH election strategies were proposed in [5-7]. The authors of [5] studied the total energy consumption as well as the optimal number of CHs in clustering network. The best proportion of CHs in the network was 5%. “Advanced” nodes with more energy than other nodes were originally called in Stable Election Protocol (SEP) proposed by [6]. The main idea of SEP was to select CH based on the weighted
election probability and its energy. This “Advanced” node had a greater probability of being selected as CH than other nodes. The election probability was calculated by the initial energy of a node. This proposal delayed the death of the first node. The clustering routing algorithm based on multi-cluster head was proposed to better balance the energy consumption among nodes for the wireless sensor network in [7].

In the above literatures, cluster heads were selected according to a certain probability. In order to further reduce energy consumption, some optimal cluster head selection strategies were proposed in [8-15]. The authors of [8] used a SEP to obtain the optimal number of elected CHs for random topology and verified that the optimal number of CHs was a fixed value. The authors in [9] focused on the specific stage of cluster establish and stable data transmission. And the Round-Robin Cluster Header (RRCH) protocol obtained the optimal number of CHs based on the analysis of the energy consumption in the steady-state phase [10]. In [11], the energy consumption of the whole round of the cluster was formulated. It involved the analysis process of the optimal number of CHs for the whole round. The authors in [12] developed a new calculation scheme for the optimal number of CHs based on the energy dissipation model. It discussed the energy consumption of data transmission in the whole round and expressed the expectation of the squared distance from the cluster members to the CH. In [13], Modified Hybrid Low Energy Adaptive Clustering Hierarchy (MHLEACH) presented a new threshold condition based on the energy consumed by the node and the maximum energy of the node for the selection of CHs, and considered the average energy of the all node in every cluster and average distance from base station when calculating the optimal number of CHs. [14] took the residual energy of the node into consideration when calculating the optimal number of CHs. In [15], the K-means clustering algorithm was introduced to obtain balanced clusters in space-constrained WSNs, and the optimal number of CHs was gained through an iterative method.

Motivated by these, we propose a dynamic cluster head (CH) number optimization scheme for two-stage selection cooperation and establish the energy consumption model for each round. By solving the energy consumption model, the optimal number of CHs in each round can be obtained. In this way, each round of transmission is carried out according to the minimum energy consumption. The simulation results show that the proposed scheme can reduce the energy consumption of the network, avoid energy waste caused by improper selection of CHs and extend the network lifetime. The main contributions of the paper are as follows:

- In clustering wireless sensor networks, a cluster head (CH) number optimization scheme for selection cooperation is proposed to avoid energy waste and the dynamic energy consumption model for each round is established in mathematical analytical form. By solving the energy consumption model, the optimal number of cluster head in each round is obtained.
- With the increase of the number of transmission rounds, the area where the survival nodes are located gradually shrinks. In the establishment of the energy consumption model, the region where the survival node is located is introduced into the model as a variable to optimize the number of cluster heads per round.
- The simulation results show the performance of the system with fixed cluster head number and optimal cluster head number. The proposed optimization scheme of cluster head number reduces energy consumption and prolongs the networks lifetime.

The rest of this paper is organized as follows: Section II describes the system model. In Section III, the energy consumption model for two-level selection cooperation in clustering networks is described and the optimization of cluster head number is formulated. Simulation results and performance analysis for energy consumption are discussed in Section IV. Section V concludes the paper.

2. System model
We consider a model as shown in Figure 1, which consists of N sensor nodes distributed randomly in a square area \((M \times M)\) and a sink node d located the centre. It is assumed that the sensor node \(S_i\) has initial energy \(E_{s0}\). The channels model between any two nodes are seen as Rayleigh fading and the instantaneous channel gain between \(S_i\) \((i=1,2,\cdots,100)\) and \(d, S_i\) and \(S_j\) \((i,j=1,2,\cdots,100, i \neq j)\) are
denoted by $\alpha_{s_i,d}$ and $\alpha_{s_i,s_j}$, respectively. Channels are independent of each other. It is supposed that the instantaneous channel gain remains unchanged in each round of data transmission and suffers additive white Gaussian noise with a mean $0$ and a variance $N_0$. Each node is equipped with only a single antenna and works in half-duplex mode. The transmission power of the sensor node is $P$. And the data transmission rate per Hz between two nodes is $V(b/s)$.

Moreover, feedback frames are adopted for data transmission within and between clusters, including acknowledgement frames (ACK) and negative acknowledgement (NACK) frames. It is used to judge whether the data transmission is successful or not. If a NACK frame is broadcast, a cooperative transmission is required.

![Network model](image)

Figure 1. Network model.

### 3. Energy Consumption Model

We adopt the two-stage cooperative transmission scheme in [16]. The whole network is divided into $K$ clusters of unequal size. Each cluster member sends data to its CH, and the CH fuses the data and sends it to the sink node. After transmission, the CH or sink node feedback ACK/NACK frame according to the received state. If a NACK frame is broadcasted, it indicates a transmission failure and a cooperative transmission begins. As the number of transmission rounds increases, the area of survivable nodes becomes smaller and smaller. If the number of CHs is constant, the network will consume too much unnecessary energy and the network lifetime will be shortened. Therefore, we first establish the network energy consumption model. The whole energy consumption is divided into two parts: one is the energy consumption at cluster set-up phase, and the other is the energy consumption at steady state phase.
3.1. Energy consumption at cluster set-up phase

There are N nodes in the network. It is supposed that there are K clusters, each cluster consists of a CH and \( \frac{N}{K} - 1 \) cluster member nodes. CHs are selected at cluster set-up phase, and each CH forms its own cluster.

The energy consumed by the CHs is divided into two parts: one is to broadcast a clustering message and the other is the feedback information received to join the cluster from the member nodes. Then the CHs create the TDMA time slot table in the cluster and advertise to their member nodes. The energy consumption of cluster member nodes includes three aspects: receiving the broadcasting message from its CH, receiving the TDMA time slots and sending the request information to join the cluster. Energy consumption of all the nodes at cluster set-up phase is

\[
E_1 = K \left[ \left( \frac{4N}{K} - 2 \right) L_1 E_{elec} + \left( \frac{N}{K} \right) L_1 e_{fs} s_{n,ci}^2 + L_1 e_{amp} d^4 \right] \tag{1}
\]

where \( E_{elec} \) denotes energy consumption of radio electronic components; \( e_{amp} \) represents the multi-path fading coefficient; \( s_{n,ci} \) is the distance between the CH and the non-cluster head node; \( L_1 \) refers to the length of the control information; \( e_{fs} \) is coefficient of free fading.

3.2. Energy consumption at steady state phase

Steady stage is mainly for data transmission. In order to reduce the loss of data in the transmission process and improve the reliability of data transmission, a two-stage cooperative transmission scheme is adopted in and between clusters. The energy consumption mainly takes place in cluster members and cluster heads. For a cluster member node \( k \), the energy for sending data to the CH is expressed as

\[
E_{k-sd} = L_2 \left( E_{elec} + e_{fs} s_{n,ci}^2 \right) \tag{2}
\]

where \( L_2 \) denotes the length of a packet. It is assumed that all packets are of equal length.

When the node \( k \) is transmitting a packet to the CH, other nodes try to decode the packet and feedback control information with \( L_1 \) bit to the node \( k \). There are \( K \) clusters and the average number of members of each cluster is \( \frac{N}{K} \). The energy consumed by the node \( k \) for receiving the feedback information is given as

\[
E_{k-r} = \left( \frac{N}{K} - 1 \right) L_1 E_{elec} \tag{3}
\]

Similarly, the node \( k \) also listens to other nodes \( \frac{N}{K} - 1 \) times and the energy consumption \( E_{k-l} \) is written as

\[
E_{k-l} = \left( \frac{N}{K} - 1 \right) L_2 E_{elec} \tag{4}
\]

If the data transmission of a cluster member nodes (except \( k \)) fails, it is assumed that the node \( k \) becomes the cooperative forwarding node with a probability of \( P_1 \), then the energy consumed by the node \( k \) for cooperative forwarding \( E_{k-cf} \) is given as

\[
E_{k-cf} = P_1 L_2 \left( E_{elec} + e_{fs} s_{n,ci}^2 \right) \tag{5}
\]

where \( P_1 = \frac{W}{X} \). The \( W \) means that the number of failed to data transmission in each round of the cluster, the \( X \) stands for the number of data transmission within the cluster per round.

When the node \( k \) completes the transmission, the energy consumed by the node for receiving the feedback information of whether the cooperative transmission from the cluster head is successful or not is

\[
E_{k-rfi} = P_1 L_1 E_{elec} \tag{6}
\]

Then the total energy consumed by the node \( k \) is
The energy consumption $E_2$ of not-CH nodes in a round is
\[ E_2 = (N-K) \left[ \frac{N}{K} - 1 + P_1 \right] E_{\text{elec}} \sum_{i=1}^{2} L_i + L_2 e_{fs} d_{n,c_i}^2 (1 + P_1) + L_2 E_{\text{elec}} \]

(8)

During the process of data transmission in the steady stage, the cooperative CH node will have the following actions. The energy consumed by the cooperative CH in receiving cluster member nodes information $(K-1)$ times can be written as
\[ E_{c-\text{CH-r}} = L_2 E_{\text{elec}} (K-1) \]

(9)

The energy consumed by the cooperative CH to feedback ACK/NACK information to other CHs $(K-1)$ times can be expressed as
\[ E_{c-\text{CH-f}} = L_1 E_{\text{elec}} + e_{fs} d_{c_i,c_j}^2 \] for $K-1$ times

(10)

where $d_{c_i,c_j}$ denotes the distance between the CH and the cooperative CH. It is assumed that the probability of the CH cooperation is $P_2$, the number of times to receive the cooperation data is $P_2 \times \frac{N}{K}$, and the energy consumption $E_{c-\text{CH-rd}}$ is as shown in equation (11).
\[ E_{c-\text{CH-rd}} = P_2 L_2 E_{\text{elec}} \left( \frac{N}{K} \right) \]

(11)

The energy consumed by the CH for receiving cooperation feedback information ACK/NACK $P_2 \times \frac{N}{K}$ times is
\[ E_{c-\text{CH-rf}} = P_2 L_1 E_{\text{elec}} \left( \frac{N}{K} \right) \]

(12)

When the CH receives the data that needs to be cooperatively transmitted, data aggregation is performed, where the data aggregation rate is $m$, and the CH can fuse up to $\frac{N}{K}$ data, then $E_{\text{CH-ad}}$ is the energy consumed by the CH data aggregation. It is expressed as
\[ E_{c-\text{CH-ad}} = L_2 E_{DA} \left( \frac{N}{K} \right) \]

(13)

After data aggregation, the energy consumed by the CH send data to the base station is
\[ E_{\text{CH-sad}} = \frac{N}{K} L_2 m E_{DA} \left( E_{\text{elec}} + e_{fs} d_c^2 \right) \]

(14)

where $d_c$ is the distance between the CH and the base station. After data transmission, the CH receives the feedback ACK/NACK from the base station and the energy consumption $E_{c-\text{CH-r-BSf}}$ is written as
\[ E_{c-\text{CH-r-BSf}} = L_1 E_{\text{elec}} \]

(15)

The energy consumed by the CH to monitor and decode the data of other CHs data $(K-1)$ times is
\[ E_{c-\text{CH-md}} = (K-1) L_2 E_{\text{elec}} \]

(16)

The energy consumption of the CH for receiving feedback $(K-1)$ times from other cluster nodes during transmission is
\[ E_{c-\text{CH-rf}} = (K-1) L_1 E_{\text{elec}} \]

(17)

The energy consumed by the CH in cooperative data forwarding is
\[ E_{c-\text{CH-f}} = P_2 L_2 \left( E_{\text{elec}} + e_{fs} d_c^2 \right) \]

(18)
where $P_2$ is the probability of cooperation between clusters in each round, i.e. $P_2 = \frac{Y}{Z}$. The $Y$ in $P_2$ means that the number of data transmission failures per round, the $Z$ in $P_2$ means that the number of data transmission per round. The energy consumption $E_{CH-r-cf}$ of the CH receives cooperation feedback is

$$E_{CH-r-cf} = P_2 L_1 E_{elec}$$

The total energy consumed by the CH in a round as follow

$$E_{CH} = \left[ P_2 \left( \frac{N}{K} + 1 \right) + 2(K-1) \right] E_{elec} \sum_{i=1}^{2} L_i + \left( P_2 + mE_{DA} \right) \left( \frac{N}{K} \right) L_2 e_f d_i^2 + (1 + mE_{elec}) L_2 E_{DA} \left( \frac{N}{K} \right) + (K-1) e_f d_{i,cj}^2 + E_{elec} L_1$$

The energy consumption $E_3$ of CHs in a round is given by

$$E_3 = K \left\{ \left[ P_2 \left( \frac{N}{K} - 1 \right) + 2(K-1) \right] E_{elec} \sum_{i=1}^{2} L_i + \left( P_2 + mE_{DA} \right) \left( \frac{N}{K} \right) L_2 e_f d_i^2 \right\}$$

The total energy consumption $E$ in a round can be obtained equation (23) by equation (1), (8), (22).

$$E = \left( \frac{N^2}{K} + 2K^2 + 2N - 2K \right) L_1 E_{elec} + \left( \frac{N^2}{K} + 2K^2 - 2K - N + NmE_{DA} \right) L_2 E_{elec}$$

$$+ NL_2 mE_{DA} e_f d_i^2 + (N-K) \left\{ P_1 E_{elec} \sum_{i=1}^{2} L_i + (1 + P_1) L_2 e_f d_{n,cj}^2 \right\}$$

$$+ (N+K)P_2 L_2 E_{elec} \sum_{i=1}^{2} L_i + KP_2 L_2 e_f d_i^2 + NL_2 E_{DA}$$

$$+ K(K-1) L_1 e_f d_{i,cj}^2 + N L_1 e_f d_{n,cj}^2 + K L_1 e_{ampd}^4$$

It is assumed that the entire network area covered by a wireless sensor network is $M \times M$, the number of CHs is $K$, and the CH is located in the centre of the area. Then for any region with different shapes, all nodes contained in it have equal status, and the distribution probability is $\rho(x,y)$. It is also supposed that all sensor nodes in the region are uniformly distributed and the distribution probability of nodes in any sub-region can be expressed as $p=1/(M^2/K)$. We derive the mathematical expectation value of the squared distance between the CH node and the base station. It is written as

$$E' = \left( 4K - 2 \frac{N^2}{K} + P_2 - P_1 \right) E_{elec} \sum_{i=1}^{2} L_i - (1 + P_1) L_2 e_f \frac{M^2 N}{2 \pi K}$$

$$+ P_2 L_2 e_f \frac{M^2}{6} + (2K-1) L_1 e_f \frac{9M^2}{16} + L_1 e_{ampd}^4$$

$E[d_{i,cj}^2]$ and $E[d_{n,cj}^2]$ are the mathematical expected values of the squares of $d_{i,cj}^2$ and $d_{n,cj}^2$, respectively, they can be obtained from the literature [9].

In order to obtain the minimum value of energy consumption in a round, the energy consumption value is derived from $K$ as in equation (24). Make $E' = 0$, solve the value of $K$ using the rooting formula. The optimal number of CHs in each round can be obtained by calculating the optimal number of CHs at the beginning of each round.
$$E[d_c^2]=\iint \left[\left(x-\frac{M}{2}\right)^2 + \left(y-\frac{M}{2}\right)^2\right] p(x,y) \, dx \, dy$$

$$=\frac{1}{M^2} \left[ \frac{1}{3} x^3 M - \frac{1}{2} x^2 M^2 + \frac{1}{3} M^3 x \right]_0^M = \frac{1}{6} M^2$$  \hspace{1cm} (24)$$

### 4. Simulation Results

In this section, we verify system performance of the proposed scheme in term of outage probability as well as network lifetime. The simulation is carried out in MATLAB. The transmission rate $V$ per Hz between two nodes is set to 1 b/s. All channels obey Rayleigh fading with a variance of 0.2. See Table 1 for other simulation parameters.

| Simulation parameters | Values            |
|-----------------------|-------------------|
| Number of nodes       | 100               |
| Distribution region   | $100 \times 100$  |
| Sink node location    | (50,50)           |
| Packet size           | 4000bit           |
| Control message length| 32bit             |
| Initial energy        | 1J                |
| Simulation rounds     | 2000              |
| $E_{elec}$            | 50 nJ/bit         |
| $e_{fs}$              | 10 pJ/bit $\times m^2$ |

We compare the number of surviving nodes of the proposed scheme called ONCH with the fixed CH number (FNCH) in different rounds with $\text{SNR}=1$ and $\text{SNR}=10$. The results are shown in figure 2 and figure 3. The fixed number of CHs $K$ is set to 10 in FNCH scheme. It can be seen from figure 2 and figure 3 that in any round, the proposed scheme performs better than the FNCH scheme. The limitation of the FNCH scheme is that the number of CHs can be arbitrarily selected without considering the special environment of the network. It is considered that as the transmission progresses, the area of the surviving nodes decreases in ONCH scheme. As the number of survival node decreases, the number of cluster heads is dynamically adjusted to minimize network energy consumption. Therefore, it has more surviving nodes than FNCH in the same transmission round.
To test whether the minimum energy consumption of our proposal will affect the transmission reliability, the comparison of outage probability between FNCH and ONCH is shown in figure 4. In addition, the outage probability of direct transmission (DT) and cooperative transmission (CT) under these two schemes is given for comparison. There is almost no difference in the outage probability for the two schemes in DT and in CT. It can be seen from figure 4 that the proposed ONCH scheme can guarantee the transmission reliability with the lowest energy consumption.
Figure 4 compares the outage probability of the network between FNCH and ONCH. It can be found that ONCH has more energy left over than FNCH in the same SNR. The reason is that ONCH optimizes the number of cluster heads, so that each round of transmission can be carried out with the lowest energy consumption. However, FNCH always transmits data with a fixed number of CHs. When the number of the survival node is small, more clustering results in an increase in energy consumption. It also can be seen that there is a bigger gap between the two schemes at low SNR. But with the SNR decreases, the gap between the two schemes gradually increases. That is because at low SNR, direct transmission often fails and requires frequent cooperative transmission. It takes more energy to
complete the same number of packets. The feedback-based ONCH scheme takes the energy consumption into the model and chooses the optimal number of CHs for each round. The more times it transmits, the more energy it saves. So, the curve of ONCN is higher than FNCH at low SNR.

5. Conclusion
This paper proposes a dynamic cluster head (CH) number optimization scheme for two-stage selection cooperation in wireless sensor nodes to minimize energy consumption. We formulate the energy consumption model for each round and take the area of the survivable nodes into account. By solved the model, the optimal number of CHs is obtained. In this way, all transmissions take place at the lowest energy consumption. Simulation results verified that the proposed scheme can effectively improve energy efficiency and extend the network lifetime.

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