IEICE TRANS. COMMUN., VOL.E107–B, NO.2 FEBRUARY 2024

PAPER

An Adaptive Energy-Efficient Uneven Clustering Routing Protocol for WSNs

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SUMMARY Aiming at the problem of “energy hole” caused by random distribution of nodes in large-scale wireless sensor networks (WSNs), this paper proposes an adaptive energy-efficient balanced uneven clustering routing protocol (AEBUC) for WSNs. The competition radius is adaptively adjusted based on the node density and the distance from candidate cluster head (CH) to base station (BS) to achieve scale-controlled adaptive optimal clustering; in candidate CHs, the energy relative density and candidate CH relative density are comprehensively considered to achieve dynamic CH selection. In the inter-cluster communication, based on the principle of energy balance, the relay communication cost function is established and combined with the minimum spanning tree method to realize the optimized inter-cluster multi-hop routing, forming an efficient communication routing tree. The experimental results show that the protocol effectively saves network energy, significantly extends network lifetime, and better solves the “energy hole” problem.

key words: *wireless sensor networks, energy efficiency, adaptive algorithm, uneven clustering*

1. Introduction

Wireless sensor networks (WSNs) are widely used in various fields such as intelligent transportation, medicine and health, smart homes, infrastructure condition detection, modern agriculture, industry and military defense [1]–[3]. The nodes are usually deployed in harsh and dangerous monitoring areas, such as deep sea, desert, tropical rainforest, etc., and are generally powered by miniature batteries [4]. As nodes close to the base station (BS) are required to take on more data forwarding tasks [5], energy will be exhausted prematurely, people often cannot replace the sensor node battery in time, thus forming an “energy hole” that will fail the surrounding communication links and reduce the network lifetime [6]. Therefore, it is of great theoretical and practical significance to study WSN energy saving solutions, maximise the network lifetime and fully utilise all nodes in the network.

WSN routing protocol aims to optimize the path selection of the entire network, reduce the unnecessary energy consumption of sensing nodes in the communication link, improve data transmission reliability of wireless sensor networks, balance node energy consumption, enhance adaptive capacity and maximize the network life, which is currently a research hotspot of WSN energy-saving theory and technology [7].

Among the WSN routing protocols, clustering-based hierarchical routing is the current mainstream [8], [9], and clustered routing protocols have better scalability and have obvious advantages in reducing network energy consumption. Heinzelman W. et al. [10] proposed the low-energy adaptive clustering hierarchy (LEACH) protocol and used the idea of clustering, it is relatively simple and only suitable for single-hop small-scale WSNs, and the data overhead is greatly reduced by data aggregation within the cluster, its shortcoming is that it is essentially a uniform cluster routing protocol, i.e. the energy of the cluster head (CH), which is farther away from the BS, is rapidly depleted, thus reducing the network lifetime [11]. For multi-hop large-scale WSNs, if a uniform cluster routing protocol is used, the closer CH is to the BS, the more frequently it communicates, the faster it will die due to rapid energy exhaustion, forming an “energy hole” and rendering the entire network unusable. Soro et al. [12] took the lead in proposing the unequal clustering size protocol, which uses unequal clustering to balance the energy consumption of CHs and extend the network lifecycle. Ye NM et al. [13] proposed the energy-efficient clustering scheme (EECS) routing protocol based on an uneven clustering method. Its communication method is single-hop communication from CH to BS, and ordinary nodes not only consider the distance from CH when selecting the CH, they also consider the distance from CH to BS, but it does not achieve energy balance between nodes as a whole. Large WSNs that use single-hop EECS routing protocols can quickly run out of energy at CHs that are far from BS, resulting in uneven network energy consumption and reduced network lifetime. Based on the EECS routing protocol, research on multi-hop uneven cluster routing protocols for large wireless sensor networks [14]–[16] has emerged.

Early mainstream multi-hop uneven cluster routing protocols [14] set different competition radius based on the distance between nodes and BS to limit the cluster size and solve the “energy hole” problem. Li C. et al. [15] proposed energy-efficient uneven clustering protocol (EEUC). This protocol combines uneven clustering and multi-hop ideas, and uses the uneven competitive radius clustering method to achieve more pairs of clusters close to the BS and a relatively small

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Manuscript received June 7, 2023.
Manuscript publicized January 15, 2024.

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DOI: 10.23919/transcom.2023EBP3097

number of ordinary nodes, so that these CHs can better save energy and achieve energy-balanced inter-cluster communication, which effectively solves the "energy hole" problem. However, the protocol does not consider the balance of the number of ordinary nodes in the cluster, and the energy consumption tends to vary greatly between clusters. Jiang C. et al. [16] proposed distributed energy-balanced unequal clustering protocol (DEBUC). It sets different competition radius based on the candidate CH positions, and uses the greedy algorithm to find the optimal multi-hop data transmission path in the CH, effectively reducing each node's energy consumption and extending the network lifecycle. Literature [15], [16] in CH competition, due to the need to set different competition radius, the candidate CH broadcast more rounds, which will consume more energy; in addition, the CH selection algorithms in such literature do not consider factors such as node residual energy and node density, and the final CH selected is not necessarily the optimal CH.

In response to these shortcomings, some researchers have added consideration of other influencing factors alongside the competitive radius as an influencing factor. Fang W. et al. [17] proposed LEACH based on partitioning and energy consumption balance protocol. It partitions according to the distance between sensor nodes and BS, making the CH selection in different partitions more targeted; At the same time, the distance factor and residual energy factor are introduced to control the competition radius of candidate CHs, so that the size of clusters is more reasonable and the "energy hole" problem is better solved. However, the algorithm does not consider information about the neighbor nodes when calculating the competition radius, making it hard to achieve energy balance within a cluster. Li Z. et al. [18] proposed Energy-balanced muti-hop cluster routing based on energy acquisition. It calculates the CH weights based on node energy and the distribution of neighboring nodes, and uses particle swarm optimization algorithms to design routing strategies to achieve energy-balanced networks, but the protocol is still deficient in extending network lifetime. Pan Y. et al. [19] proposed an energy-efficient cluster routing algorithm for wireless sensor networks. The algorithm introduces node energy factor and the neighbor node density factor to achieve optimal CHs selection;the gradient descent method is used to optimally select relay nodes to achieve inter-cluster multi-hop routing optimization. However, the algorithm uses a cyclic clustering method, so the influence of the clustering cycles of the network on energy consumption needs to be further studied. Yu X. et al. [20] proposed an uneven clustering routing protocol based on dynamic competition radius. The protocol indirectly achieves uneven clustering in areas close to BS through a dense clustering method based on factors such as the node's distance from BS and the node's residual energy; the energy consumption of the CH selection process is reduced by introducing predecessor and successor energy consumption factors in the competition radius. Since the network nodes of this protocol are theoretically deployed in a random and uniform manner, this results in nodes closer to BS consuming more energy, making it difficult to achieve a balanced energy consumption across the network. Man Gun Ri et al. [21] propose an energy-efficient hierarchical clustering routing protocol. It comprehensively considers various factors such as node residual energy, distance from node to BS, neighbor node degree, link state and predicted harvest energy to select the optimal CH and optimal relay node; in the data transmission stage, it reduces node energy consumption through adaptive adjustment of transmission power technology to achieve balanced network energy consumption. Obviously, the protocol's approach to achieving network energy balance relies heavily on the network underlying hardware design and software functionality of the sensor nodes and has little relevance to the design of the routing protocol itself.

Synthesizing the advantages and disadvantages of related literature, this paper proposes an adaptive energy-efficient balanced uneven clustering (AEBUC) routing protocol for large-scale WSN monitoring areas. In this paper, an uneven network model is designed and deployed, which adaptively adjusts the competition radius through the candidate CH node positions and neighboring node densities to achieve scale-controlled adaptive optimal clustering. Comprehensively consider the energy relative density and the candidate CH relative density to achieve dynamic selection of CHs. In inter-cluster communication, the relay communication cost function is established, and the inter-cluster multi-hop route with low communication cost and high energy efficiency is selected by combining the method of minimum spanning tree. The experimental results show that the protocol solves the "energy hole" problem very well.

The rest of the paper is structured as: Section 2 presents models and methods for representing WSN based on graph models. Section 3 provides a comprehensive description of the AEBUC routing protocol, including the CH dynamic selection, adaptive uneven clustering algorithms, and inter-cluster multi-hop path selection algorithms. Section 4 analyses the performance of this routing protocol by designing experiments. Section 5 summarizes the key findings and provides future research directions.

2. WSN Representation Models and Methods

2.1 WSN Structure Representation Method Based on Graph Model

In this paper, the WSN-based monitoring area is abstracted as a sector centered on the BS ($0 < \theta < 360°$). A monitoring sector with an amplitude angle of 90° is taken in this paper [22]–[25], and the corresponding WSN network topology is shown in Fig. 1. It divides the monitoring area into H concentric rings, each ring being subdivided into a number of clusters of unequal size, each consisting of a CH and a number of ordinary nodes. The intra-cluster communication is as follows: ordinary nodes transmit data to the CH first, and the CH transmits data to the neighboring CH along the direction of BS, and the CH is dynamically selected based on the remaining energy of the nodes in the cluster and

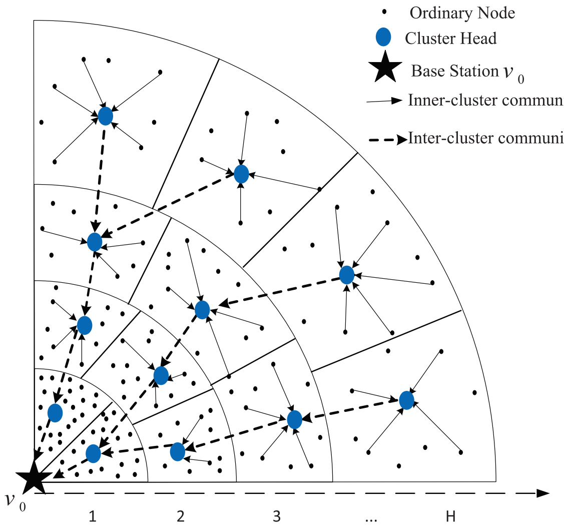


Fig. 1 WSN network structure based on graph model.

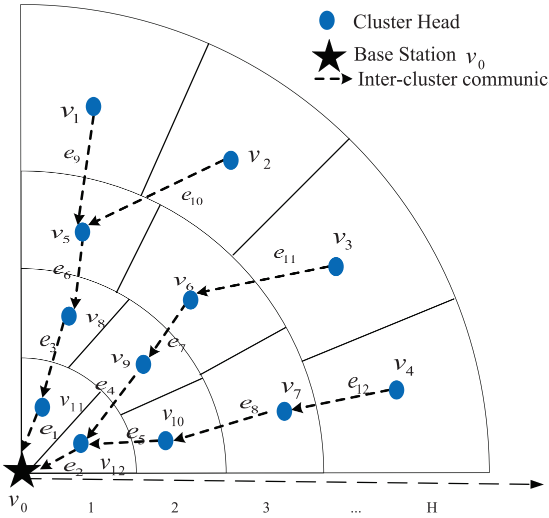


Fig. 2 WSN inter-cluster communication routing model.

their balancing strategy. From a graph-theoretic perspective, ordinary nodes within a cluster can be regarded as leaf nodes, the CH within a cluster is its parent node, and intra-cluster communication routes can be described as terminal subtrees. The WSN inter-cluster communication method is: after the CH fuses the data of each node in the cluster, the data is transmitted along the direction of BS, using a multi-hop approach, through the neighboring CH relay, and finally reaches BS. From a graph theory perspective [26]–[28], BS can be regarded as the root node of the tree, going down in order to the end CH, and the CH through which the data passes are regarded as parent-child nodes to each other, and the inter-cluster communication route can be described as the trunk of the WSN global communication. Obviously, the WSN structure can be mathematically rigorously described by using graph theoretical terms, which treats inter-cluster communication paths and intra-cluster communication paths as a routing tree.

2.2 WSN Inter-Cluster Communication Routing Representation Method Based on Graph Model

In routing protocol research, inter-cluster communication is an optimized routing tree with BS as the root, the CHs as the child nodes and energy saving as the goal. Figure 1 is now used as an example, and all ordinary nodes are ignored to form the inter-cluster multi-hop communication routing model shown in Fig. 2, which is a typical tree [29]–[32] defined as follows:

BS is represented by v_0, BS and the CH form the set of all vertices of this routing tree and is denoted as V, $V = \{v_0, v_1, v_2 \ \dots \ v_{12}\}$; The set of directed edges of the tree is denoted E, $E = \{e_1, e_2 \ \dots \ e_{11}\}$. The set V and set E form the routing tree, denoted T, $T = (V, E)$. In Fig. 2, The set V in $T = (V, E)$ has 13 elements and the set E has 12 elements, where each vertex has a unique path to BS v_0. To make the routing tree optimal, the following minimum spanning tree condition is satisfied:

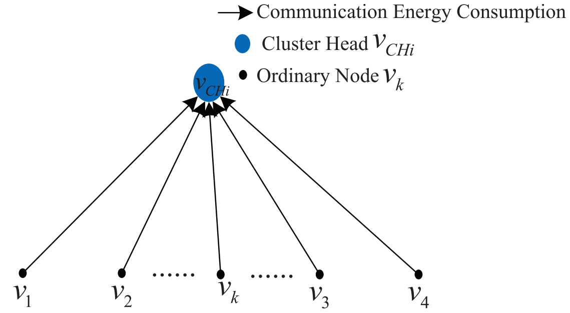


Fig. 3 WSN intra-cluster communication routing model.

$$W(v_{CHi}, v_0) = \min \sum w(e(v_{CHi}, v_{CHj})) \tag{1}$$

Where, $W(v_{CHi}, v_0)$ is the minimum energy consumption from any CH node v_{CHi} to the BS v_0; The CH nodes are denoted as v_{CHi} and v_{CHj}. Since there are many paths from CH node v_{CHi} to BS v_0 to choose from before inter-cluster routing is determined, $w(e(v_{CHi}, v_{CHj}))$ is used to denote the weight of the edge of the path that passes from the CH node v_{CHi} to BS v_0. The weight of an edge is the energy consumed by the two sensing nodes v_{CHi} and v_{CHj} forming that arbitrary edge to communicate. Clearly, $w(e(v_{CHi}, v_{CHj}))$ in this paper's study is the node communication energy consumption. Then, according to Eq. (1), all CHs v_{CHi} to the BS v_0 consume the minimum amount of energy, and an optimal routing tree with the goal of energy saving is considered to be generated.

2.3 WSN Intra-Cluster Communication Routing Representation Method Based on Graph Model

The communication routing model within any cluster of the WSN is shown in Fig. 3, where the CH node is represented by v_{CHi} and any ordinary node within the cluster is denoted as v_k. The intra-cluster communication uses a single-hop approach [33]–[35], with the ordinary node transmitting data to the CH within the cluster. To achieve maximum energy savings, CH selection should adopt a dynamic strategy, with each node being eligible for selection. To become the CH at a given time, the following conditions should be met:

$$Choose(v_{CHi}) = \min \sum w(e(v_{CHi}, v_k)) \tag{2}$$

Eq. (2) means that when any node is temporarily selected as the CH, its communication energy consumption with other nodes is calculated and whichever consumes the least energy is finally determined as the CH. In complex cases, the selection of the CH should also consider the neighboring CHs, so that the dynamic selection of the CH generates an optimal routing tree for intra-cluster communication with the goal of energy saving.

2.4 WSN Energy Model

In WSNs, the energy consumption of sensor nodes mainly includes communication energy consumption and data processing energy consumption [36]–[38]. Communication energy consumption includes data transmission energy consumption and data reception energy consumption; data processing energy consumption includes intra-cluster and inter-cluster communication data processing energy consumption.

2.4.1 WSN Node Communication Energy Model

The wireless communication simplex model used in this paper is shown in the Fig. 4 below [10], where transmitting node v_T consists of transmitting electronic circuits and power amplifiers, and receiving node v_R only consists of receiving electronic circuits when receiving, and the transmission distance between the two is l. When they transmit m bits of data, the total transmit energy consumption of transmitting node v_T is denoted as $E_{TX}(m,l)$, where the transmit electronic circuit energy consumption is denoted as $E_{TX-elec}(m)$ and the power amplification energy consumption is denoted as $E_{amp}(m,l)$. The total reception energy consumption of the receiving node v_R is denoted as $E_{RX}(m)$, and the energy consumption of the receiving electronic circuit is denoted as $E_{RX-elec}(m)$. The relationship between various energy consumption and the calculation methods are as follows.

$$\begin{aligned} E_{TX}(m,l) &= E_{TX-elec}(m) + E_{amp}(m,l) \\ &= E_{elec} \times m + \varepsilon \times m \times l^n \end{aligned} \tag{3}$$

Where, E_{elec} represents the energy lost in the transceiver electronic circuit, ε represents the power amplification energy factor. Depending on the transmission distance l, either a free-space model or a multi-path fading model is used, with the corresponding power amplification energy factor ε denoted as $\varepsilon_1 \varepsilon_2$ respectively. Define the transmission distance threshold as l_0, $l_0 = \sqrt{\frac{\varepsilon_1}{\varepsilon_2}}$. In general, when $l < l_0$, $n = 2$; when $l \geq l_0$, $n = 4$.

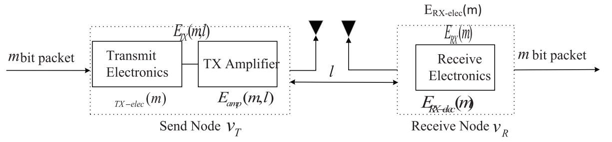


Fig. 4 WSN node communication energy model.

$$E_{RX}(m) = E_{RX-elec}(m) = E_{elec} \times m \tag{4}$$

2.4.2 WSN Data Fusion Energy Model

In WSN clustered routing protocols, data fusion [39] is used to reduce the amount of data transmission and reduce the energy consumption of the network. Due to the large variability of data between clusters, data fusion for inter-cluster communication is not considered in this simulation [10], [16], [20]. The data fusion model within a cluster is assumed to be:

Each node within a cluster transmits m bit data to the CH, and the CH fuses several m bit data received within the cluster into m bit packets. The energy required to fuse m bit data within a WSN cluster is:

$$E_R(m) = E_{DA} \times m \tag{5}$$

Where, E_{DA} is the energy consumed to fuse a unit bit of data.

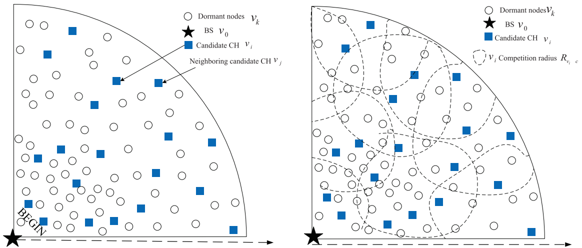
Referring to Figs. 1, 2 and 3, when using graph theory to describe the WSN structure, intra-cluster and inter-cluster communication route spanning trees, the weights of the edges of the corresponding graphs, which will be calculated based on the node identity (CH, ordinary node), the relationship between the nodes by the combined statistics from the various energy consumptions mentioned above.

3. AEBUC Routing Protocol Model and Algorithm

In this paper, we synthesize the advantages and disadvantages of related literature, improve the related LEACH protocol in literature [5], [10], and propose the AEBUC routing protocol for WSNs. The main innovation is the use of a dynamic CH selection algorithm, which enables a more rational distribution of CH, adjusts the competition radius, and achieves optimized clustering with controllable size. Based on the principle of energy-balanced, multi-hop routes between clusters are reasonably constructed to generate an optimized route tree.

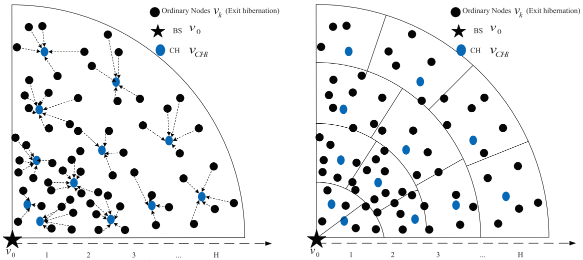
3.1 Energy-Efficient Dynamic CH Selection and Adaptive Uneven Clustering Algorithm

The principle mechanism of the dynamic CH selection and adaptive uneven clustering algorithm proposed in this paper is shown in Fig. 5. In the intra-cluster communication, its CH dynamic selection algorithm considers not only the residual energy of the nodes, but also the distance between the nodes



(a) The node that satisfies the thresholds of the residual energy of the candidate CH and the composite factor of the candidate CH becomes the candidate CH v_i . The other ordinary nodes enter the dormant state until the CH selection is completed

(b) Candidate CH v_i broadcasts COMPETITIVE_MSG information (node ID, competition radius R_C and remaining energy $E_{v_i\_resi}$) with $R_{v_i\_c}$ as the broadcast radius to run for the CH, and declares itself as the CH v_{CHi} with the broadcast time $T(i)$



(c) After the completion of CH selection, the message CH_ADV_MSG of successful selection is broadcasted, the ordinary node exits the dormant state and choose the nearest CH, and the WSN intra-cluster communication route is formed.

(d) uneven cluster formation

Fig. 5 Principle and mechanism of dynamic CH selection and adaptive uneven clustering.

and the BS and the node density to make the CH distribution more reasonable; its adaptive clustering algorithm adjusts the competition radius according to the distance from the nodes to the BS and the size of the node density to achieve adaptive optimal clustering with controllable scale. The specific description is as follows:

1) Candidate CH generation method

As shown in Fig. 5(a), during the initialization stage of network routing, BS broadcasts a “BEGIN” packet to the monitoring area, and all nodes in the WSN will perceive the RSSI of the “BEGIN” packet. To minimize the effect of random errors, RSSI values are averaged over several measurements, which is monotonically decreasing in size with respect to the distance to the BS. The candidate CH synthesis factor $\phi(i)$ is now defined to control the number of candidate CHs in each round, which is related to the RSSI of the “BEGIN” group perceived by node v_i, the residual energy $E_{v_i\_res}$ of node v_i, and the distance $d(v_i, v_0)$ from node v_i to BS v_0.

$$\begin{aligned}\phi(i) &= f(RSSI, E_{v_i\_res}, d(v_i, v_0))\\ &= p_\mu \times \frac{E_{v_i\_res}}{E_0} \times \frac{d_{\max}-d(v_i,v_0)}{d_{\max}-d_{\min}}\end{aligned} \tag{6}$$

Where, p_μ is the RSSI-based candidate CH probability, which means that a node becomes a candidate CH with probability p_μ when RSSI is considered, $p_\mu = P(X \le RSSI)$, X is a continuous random variable about the RSSI of the BS, and for simplicity treat X as normally distributed with the signal strength received at the farthest node as the central moment, then $0.5 \le p_\mu \le 1$; E_0 is the initial energy of the node and $d_{\max}, d_{\min}$ are the maximum and minimum distances from all nodes to the BS v_0 respectively.

In order to improve computational efficiency, the following conditions should be satisfied for node v_i to become a candidate CH:

$$Choose(v_i) = \{E_{v_i\_res} > E_{res\_th} \ \ \& \ \ \phi(i) > \phi_{th}\} \tag{7}$$

where, E_{res_th}, ϕ_{th} are the thresholds for the residual energy of the candidate CH and the candidate CH synthesis factor, respectively.

$$E_{res\_th} = E(E_{v_i\_res}) \tag{8}$$

$$\phi_{th} = p_\mu E(\phi(i)) \tag{9}$$

$E(E_{v_i\_res})$ represents the mathematical mean of the remaining energy $E_{v_i\_res}$ of node v_i. $E(\phi(i))$ represents the mathematical mean for the candidate CH composite factor $\phi(i)$. p_μ in Eq. (9) guarantees non-uniformity in the selection of candidate CHs, and the larger the $d(v_i, v_0)$ the more sparse.

The candidate CH generation algorithm pseudocode is described as follows:

```
Algorithm 1: Candidate CH generation method
Input: RSSI; the residual energy $E_{v_i\_res}$ of node $v_i$; the
       distance $d(v_i, v_0)$ from node $v_i$ to BS $v_0$.
Output: Set of candidate CHs $V_{candidate}$
Calculate the value of $\phi(i)$ according to Eq. (6)
$E_{resi\_th} \leftarrow E(E_{v_i\_res})$,$\phi_{th} \leftarrow p_\mu E(\phi(i))$
for every node $v_i$ in network do
    if $E_{v_i\_res} > E_{res\_th}$ & $\phi(i) > \phi_{th}$ then
        Add node $v_i$ candidate cluster set $V_{candidate}$
    end
end
return $V_{candidate}$
```

2) CH generation method

As shown in Fig. 5(b), any candidate CH v_i broadcasts *COMPETITIVE_MSG* information with a constant R_C as the broadcast radius, which contains the candidate CH v_i's own ID, the contention radius $R_{v_i\_c}$ and the remaining energy $E_{v_i\_res}$, where $R_{v_i\_c}$ is calculated as follows:

$$\begin{aligned}R_{v_i\_c} &= f(d(v_i, v_0), N_{v_i\_neighbor})\\ &= (1 - C\frac{d_{\max}-d(v_i,v_0)}{d_{\max}-d_{\min}} - C\frac{N_{v_i\_neighbor}}{N_{alive}})R_C\end{aligned} \tag{10}$$

Where, the parameter $C \in (0, 1)$, indicating the degree of non-uniformity of clustering, can be chosen by experimental optimization; $v_i\_neighbor$ represents the neighbor candidate CHs within the broadcast radius R_C of candidate CH v_i. $N_{v_i\_neighbor}$ represents the number of its neighbor candidate CHs; N_{alive} represents the number of all candidate CH nodes, $N_{alive} = |V_{candidate}|$. Equation (10) shows that the closer the candidate CH v_i is to the BS and the higher the density of its neighboring candidate CHs, the smaller its competition radius $R_{v_i\_c}$ is and the smaller its cluster formation area is, achieving adaptive optimal clustering with controllable scale.

When the competitive radius of candidate CH v_i is $R_{v_i\_c}$, the set of its neighbor candidate CHs $V_{R_{v_i\_c\_neighbor}}$ is defined as follows:

$$V_{R_{v_i\_c\_neighbor}} = \left\{v_j \in V_{candidate} | d(v_i, v_j) < \max(R_{v_i\_c}, R_{v_j\_c})\right\} \tag{11}$$

Where, $d(v_i, v_j)$ is the distance between candidate CH v_i and its neighbor candidate CH v_j, R_{vi_c} and R_{vj_c} are the competing radii of candidate CHs v_i and v_j, respectively.

For any candidate CH v_i, it forms a competing set of CHs with its neighboring set of selected CHs, $V_{R_{v_i\_c\_neighbor}}$ denoted as $V_{R_{v_i\_c}}$, ($V_{R_{v_i\_c}} = V_{R_{v_i\_c\_neighbor}} \cup \{v_i\}$).

For any candidate CH $v_l \in V_{R_{v_i\_c}}$, a CH selection synthesis factor T_{v_l} is introduced, which indicates whether v_l becomes a CH evaluation indicator, and dynamic CH selection is completed based on this factor. In the CH competition set $V_{R_{v_i\_c}}$, node v_{CH}, which becomes the CH, has the smallest CH selection composite factor $T_{v_{CH}}$, i.e. it satisfies Eq. (12).

$$T_{v_{CH}} \leq T_{v_l} \tag{12}$$

The synthesis factor T_{v_l} for the CH selection is calculated as follows:

$$T_{v_l} = \lambda \times \tau \times (\eta \frac{\bar{E}\ R_{vl\_c\_neighbor}}{E_{vl\_res}} + \gamma \frac{N_{alive}}{N_{R_{vl\_c\_neighbor}}}) \tag{13}$$

Where, $0.9 < \lambda < 1$, τ is the predetermined CH competition time [40], and $\eta + \gamma = 1$, represents the weight of the energy relative density and the candidate CHs relative density. $\bar{E}\ R_{v_l\_c\_neighbor}$ represents the remaining energy of the v_l -neighbour candidate CHs based on the competition radius $R_{v_l\_c}$, and $N_{R_{vl\_c\_neighbor}}$ represents the number of v_l -neighbour candidate CHs based on the competition radius $R_{v_l\_c}$. Equation (13) shows that the greater the relative density of the remaining energy of the candidate CH v_l, and the greater the relative density of neighbor candidate CHs within its competitive radius, the smaller the T_{v_l}, the greater its chance of becoming the CH, ensuring that the selection of the CH is reasonable.

The CH generation algorithm pseudocode is described as follows:

Algorithm 2: CH generation method

```
Input: Set of candidate CHs $V_{candidate}$
Output: Set of CHs $V_{v_{CH}}$
if $v_i \in V_{candidate}$ then
    $v_i$ broadcast $COMPETITIVE\_MSG$ (ID, $R_{v_i\_c}$, $E_{v_i\_res}$ )
end
else
    Sleep
end
for every $v_i \in V_{candidate}$ do
    Calculate $R_{v_i\_c}$ according to Eq. (10)
    On receiving a $COMPETITIVE\_MSG$ from $v_i \in V_{candidate}$
    if $d(v_i, v_j) < \max(R_{v_i\_c}, R_{v_j\_c})$ then
        Add $v_j$ to $v_i$ neighbor set $V_{R_{v_i\_c\_neighbor}}$
    end
end
for every $v_l \in V_{R_{v_i\_c}}$ do
    if $E_{v_l\_res} \geq \bar{E}\ R_{vl\_c\_neighbor}$ then
        Calculate $T_{v_l}$ according to Eq. (13)
    end
    else
        $v_l$ give up the CH selection and become an ordinary node $v_k$
    end
end
while the timer $\tau$ is not expired do
    if $T_{v_{CH}} \leq T_{v_l}$ then
        if hear $SUCCESS\_CLUSTERHEAD\_MSG$ from a neighbor $V_{R_{vl\_c\_neighbor}}$ then
            Give up the competition
        end
    end
    else
        $SUCCESS\_CLUSTERHEAD\_MSG(ID)$
    end
    Add $v_l$ to candidate cluster set $V_{v_{CH}}$
end
return $V_{v_{CH}}$
```

3) Ordinary node clustering methods in uneven clustering

As shown in Fig. 5(c), after the selection of CH v_{CHi} is completed, ordinary node v_k exits the dormant state and joins the CH nearest to itself based on Eq. (2), and the clustering of ordinary nodes v_k in uneven clusters is completed, and finally an optimal routing tree for intra-cluster communication with the goal of energy saving is generated.

The ordinary node clustering method pseudocode in uneven clustering is described as follows:

Algorithm 3: Clustering method of common nodes in uneven clustering

```
Input: Set of CHs $V_{v_{CH}}$, Ordinary Nodes $v_k$
Output: Optimal routing trees for intra-cluster communication
for every $v_{CHi} \in V_{v_{CH}}$ do
    All $v_{CHi}$ broadcast $CH\_ADV\_MSG$ in the cluster radius
    $v_k$ join in the cluster with the principle
    $Choose(v_{CHi}) \leftarrow \min \sum w(e(v_{CHi}, v_k))$
    send $JOIN\_SUCCESS\_MSG$ to corresponding CH $v_{CHi}$
    Optimal routing tree generation for intra-cluster communication generate
end
return intra-cluster optimal routing trees
```

4) Uneven clustering complete

As shown in Fig. 5(d), the adaptive WSN uneven clustering is completed.

3.2 Energy-Balanced Inter-Cluster Multi-Hop Routing Algorithm

Referring to Fig. 2, this paper proposes an inter-cluster multi-hop routing algorithm, based on the principles of energy balancing, which first reasonably selects the peripheral CHs, along the BS direction, constructs their edge sets with other CHs up to the BS, calculates the energy consumption of each edge using Eqs. (3)–(5), establishes the optimal relay communication cost function, and finally generates an optimized inter-cluster multi-hop routing tree satisfying Eq. (1), which can connect all CH nodes in the direction of the BS, starting from the peripheral CH. It does not lose packets, but also avoids loopback of data transmission, reducing energy consumption and balancing network energy consumption.

When the CH v_{CHi} selects its next relay CH v_{CHj}, its relay communication cost function $F(i,j)$ is calculated as follows:

$$F(i,j) = \begin{cases} \alpha \dfrac{\bar{E}_{v_{CHi\_neighbor}}}{E_{v_{CHj\_res}}} + \beta \dfrac{d^2(v_{CHj}, v_{CHi}) + d^2(v_{CHj}, v_0)}{d^2(v_{CHi}, v_0)}, & if\ i \neq j \\ \alpha \dfrac{\bar{E}_{v_{CHi\_neighbor}}}{E_{v_{CHj\_res}}} + \beta, & if\ i = j,\ d(v_{CHi}, v_0) \leq TD\_MAX \\ +\infty, & if\ i = j,\ d(v_{CHi}, v_0) > TD\_MAX \end{cases} \quad (14)$$

Where, $\bar{E}\ _{v_{CHi\_neighbor}}$ represents the mean residual energy of the neighboring CH members of CH v_{CHi}, $E_{v_{CHj\_res}}$ represents the current residual energy of neighboring CH v_{CHj}, $d(v_{CHj}, v_0)$ is the distance from neighboring CH to the BS, $d(v_{CHj}, v_0)$ is the distance between neighboring CH v_{CHj} and CH v_{CHi}, TD_MAX is the threshold from CH to BS, and α, β is the weighting factor, $\alpha + \beta = 1$.

According to Eq. (1) in Sect. 2.2, the purpose of inter-cluster multi-hop routing is to form an energy-efficient communication routing tree $T = (V, E)$. Therefore, the CH v_{CHi} selects the next relay CH to communicate with from its neighbour CHs and must satisfy the minimum relay communication cost function.

The inter-cluster multi-hop routing is shown in Algorithm 4.

3.3 AEBUC Routing Protocol Description

Combining the intra-cluster and inter-cluster communication routing algorithms in Sect. 3.1 and Sect. 3.2, the overall description of the AEBUC routing protocol is shown in algorithm 5.

Algorithm 4: Inter-cluster multi-hop routing algorithm

```
   Input: Communication connected graph $G$
   Output: Communication routing tree $T$
 1 Define the set of CH as $V_{v_{CH}}$, the set of edge weights of CH as
     $E_{v_{CH}}$. Add $v_0$ to set $V_{v_{CH}}$, $E_{v_{CH}} \leftarrow \varnothing$
 2 for every CH $v_{CHj}$ connected to the peripheral CH $v_{CHi}$ do
 3     Calculate $F(i, j)$ according to Eq. (14)
 4     if satisfy $F(i, j) = \min$ then
 5         Add $v_{CHj}$ to set $V_{v_{CH}}$, Add the weights of the edges
             to set $E_{v_{CH}}$
 6     end
 7 end
 8 for every CH $v_{CHj\_j}$ connected to the CH $v_{CHj}$ do
 9     Calculate $F(j, j\_j)$ according to Eq. (14)
10     if satisfy $F(j, j\_j) = \min$ then
11         Add $v_{CHj\_j}$ to set $V_{v_{CH}}$, Add the weights of the
             edges to set $E_{v_{CH}}$
12     end
13 end
14 if $V_{v_{CH}} = V$ then
15     end the search
16 end
17 else
18     move to line 8
19 end
20 Optimized communication routing tree $T = (V, E)$
21 return $T$
```

Algorithm 5: Clustering algorithm code of AEBUC protocol

```
   Input: the location of nodes, residual energy of nodes,
          maximum cluster radius, network average energy
   Output: Cluster structure
 1 AEBUC =Call function('algorithm1', 'algorithm2',
     'algorithm3', 'algorithm4')
```

4. Experimental Design and Results Analysis

In this paper, the proposed AEBUC algorithm is simulated and compared with the EEUC [15], DEBUC [16] algorithm under the same conditions through MATLAB 2020a. We designed three experiments to validate the routing protocols proposed in this paper. Experiment 1 is a design experiment for WSN nodes based on graph model to achieve an uneven distribution of nodes by optimizing the nodes distribution in the WSN. Experiment 2 is based on Experiment 1, and the optimal value of parameter C in the candidate CH competition radius $R_{v_i\_c}$ is experimented to determine the optimal value of C; The optimal values of the energy relative density coefficient η and the candidate relative density coefficient γ in the CH selection composite factor T_{v_l} were then optimized to determine the optimal values for both. Finally, on the basis of Experiment 2, the effectiveness of the AEBUC routing protocol proposed in this paper is verified through the WSN routing protocol performance evaluation index.

Table 1 shows the relevant experimental environment and parameter settings for WSN routing initialization, CH selection, and data processing. The parameters related to the energy consumption model are taken from the literature [10], [15], [16], and other parameters are found by multiple simulation experiments to find their optimal values.

4.1 Performance Evaluation Indicators

(1) Message complexity of the network clustering stage

The message complexity is directly related to the communication overhead during network clustering. The lower the communication overhead, the less energy is consumed

Table 1 Network environment and simulation parameters.

Parameter	Value	Parameter	Value
WSN coverage radius	$360\,m$	τ	0.4
Base station location	$(0,0)\,m$	R_C	90
Node number	400	C	0.4
Initial energy	$0.5J$	α	0.6
TD_MAX	$140m$	β	0.4
ε_1	$10\,pJ/bit/m^2$	E_{DA}	$5\,nJ/bit$
ε_2	$0.0013\,pJ/bit/m^4$	l_0	$87\,m$
η	0.45	γ	0.55

during network clustering, which is an important indicator to evaluate the network lifetime.

(2) Network lifetime

This paper analyses and validates the network lifetime by simulating the number of nodes surviving each round of the three protocols and selecting the first node death time $T_{first-dead}$, 30% node death time $T_{30\%-dead}$ and all node death times $T_{all-dead}$.

(3) Balanced energy consumption

The energy balance of a network is measured using the mean and variance of the energy of the network. The combination of the two is considered that the larger the mean and the smaller the variance, the better the energy balance of the network. Three experiments are designed to compare the performance of routing protocols by designing the total remaining energy of the network, the mean energy of the network nodes and the variance of the network energy.

(4) Routing algorithm topology

The network topology diagram is used to test whether the routing algorithm designed in this paper achieves uneven clustering and whether the resulting topology meets the design requirements for an efficient communication routing tree.

4.2 Node Distribution Design Experiments

In this paper, WSNs are set to have the following properties [10], [15], [16]:

(1) The BS is in a fixed position and has unlimited energy.

(2) Nodes are stationary after network routing initialization, all network sensor nodes have the same physical layer and link layer protocols, and each node carries the same initial energy and unique ID.

(3) All nodes have the ability to communicate and process data, and the communication power of each node can be adjusted according to the transmission distance.

(4) Nodes can achieve location awareness by receiving signal strength RSSI and calculating the distance between nodes.

When nodes are deployed randomly in WSNs, the energy consumption of CHs near the BS is greater, creating an "energy hole" problem. Therefore, in this paper, when designing and deploying an uneven network model, the density of nodes in the area close to the BS is higher, effectively equalising the network energy consumption. Figure 6 shows the uneven deployment of 400 nodes located in a radius area after network routing initialization. The BS located at (0,0) m, packet length is 4000 bit, broadcast packet length is 200 bit [10], and other simulation parameters are shown in Table 1. The small coloured circles represent the individual sensor nodes.

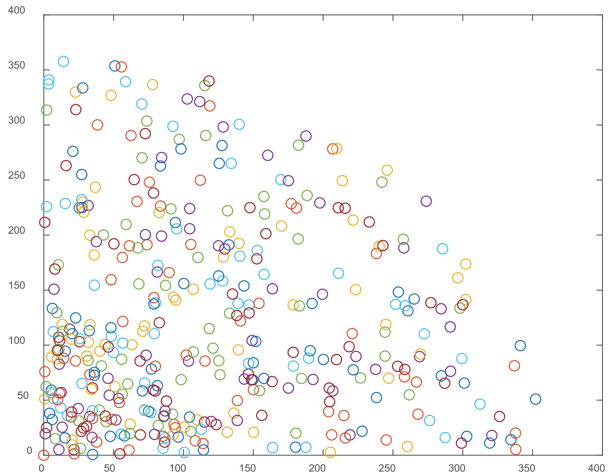


Fig. 6 Network initial node deployment diagram.

4.3 Optimization Experiments on Relevant Parameters

(1) Candidate cluster head competition radius factor

The value of the non-uniformity parameter C in the candidate CH competition radius $R_{v_i\_c}$ directly affects the degree of uneven clustering of WSNs. Therefore, based on the above experimental environment and network node deployment model, for the value of C, the C traversal experiment was designed to calculate the optimal value of the non-uniformity parameter C by the first node death time.

$C \in (0,1)$, From Fig. 7, it can be seen that at $C = 0$, the clusters formed are uniform and the first node has the earliest time of death, i.e. uniform clustering causes uneven energy consumption of the WSN and affects the network lifetime. When $0 < C < 0.4$, The degree of uneven clustering of the network gradually strengthens, indicating that the uneven clustering algorithm gradually balances the network energy consumption and the first node death time gradually extended. When $C = 0.4$, the degree of uneven clustering of the network reaches a maximum and the lifetime of the nodes in the network also reaches a maximum at this time; When $0.4 < C < 1$, the radius of competition for candidate CHs decreases, the number of CHs increases, the number of generated clusters increases and the balance of network energy consumption gradually decreases. Therefore, in this paper, after the other parameters are determined and based on the above experimental data, $C = 0.4$ is taken as the optimal value, when the first round of node death is slower, and the value is more appropriate.

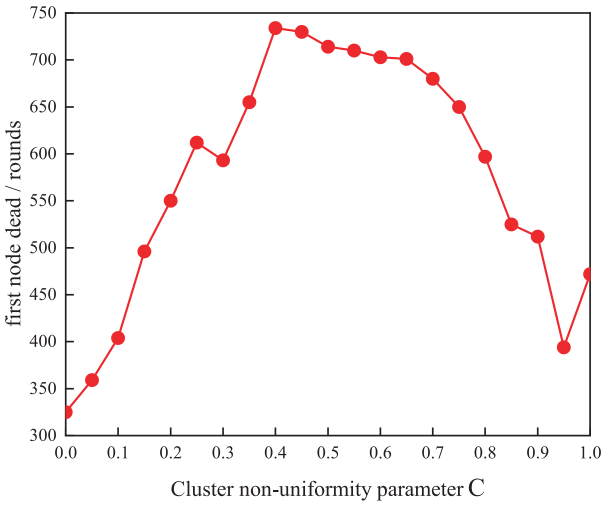


Fig. 7 The relationship between the first round node death time and the parameter.

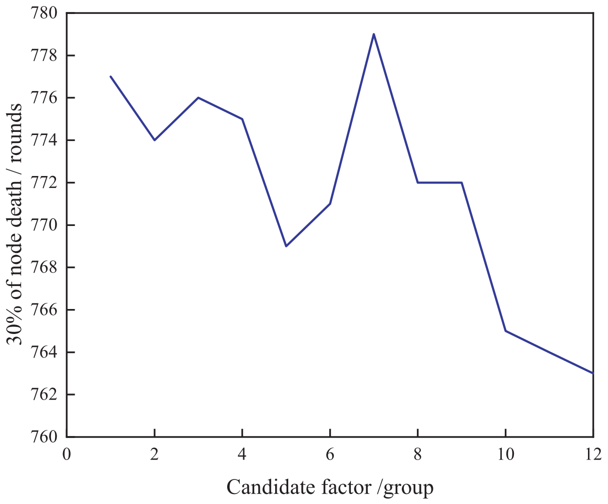


Fig. 8 Relationship between candidate coefficient and 30% node failure time.

Table 2 Competition function coefficient candidate group.

No.	v_l Energy relative density coefficient η	v_l candidate CH relative density coefficient γ
1	0.15	0.85
2	0.20	0.80
3	0.25	0.75
4	0.30	0.70
5	0.35	0.65
6	0.40	0.60
7	0.45	0.55
8	0.50	0.50
9	0.55	0.45
10	0.60	0.40
11	0.65	0.35
12	0.80	0.20

(2) CH selection composite factor coefficient

The composite factor T_{v_l} for the CH selection in Eq. (13) consists of two factors, The optimal values of the energy relative density coefficient η and the candidate CH relative density coefficient γ, respectively; The top 12 groups with better performance based on a sum of two coefficients of 1, traversal and simulation experiments are listed in Table 2.

The experimental results obtained are shown in Fig. 8.

From Fig. 8, the WSN lifetime is longest when the coefficients of Group 7 are selected. Among them, the first energy relative density coefficient accounts for a relatively small proportion. This is due to the fact that in the candidate CH selection stage, the element of node residual energy is already considered in the candidate CH synthesis factor, and the residual energy of the candidate CH obtained by this condition is more, and at the same time, in order to achieve energy balance, most of the nodes in the cluster should take up the task of CH, so the influence of this term on the selection of the CH is relatively small, and the coefficient assigned is relatively small. For the candidate CH relative density coefficient of v_l, the coefficient of the candidate CH relative density is relatively large because of the uneven deployment of nodes, which results in a higher density of nodes at locations close to the BS. This factor not only affects the communication energy consumption of the CH within the cluster, but also affects the energy consumption of ordinary nodes within the cluster.

4.4 AEBUC Routing Protocol Performance Verification and Analysis

(1) Message complexity of network clustering

During network clustering, if the number of nodes in the WSN is N, then there are $p_\mu \times N$ nodes that become candidate CHs and broadcast a total of $p_\mu \times N$ COMPETITIVE_MSG messages to participate in the CH competition. Assuming that Q CHs are selected, there are Q SUCCESS_CLUSTERHEAD_MSG messages and Q CH_ADV_MSG messages, and ordinary nodes broadcast $N - Q$ JOIN_SUCCESS_MSG messages to join the cluster. Therefore, the total message overhead is:

$$p_\mu N + Q + Q + N - Q = (p_\mu + 1)N + Q \tag{15}$$

The message complexity is $O(N)$, indicating that AEBUC has low message overhead, which can save WSN energy and realize the efficient use of node energy.

(2) Network lifetime

The WSN network lifetime is as described in Sect. 4.1 performance evaluation indicators, and Fig. 9 compares the change in surviving nodes over time for the three algorithms in a 400-node WSN. As can be seen from the Fig. 9, in terms of time to death of the first node $T_{first-dead}$ in the WSN, AEBUC improves by 146% over EEUC and 43% over DEBUC; In terms of time to death for 30% of the nodes $T_{30\%-dead}$ in the network, AEBUC improved 118% over EEUC and 41% over DEBUC; In terms of time to death for all nodes $T_{all-dead}$ in the network, AEBUC improved 117% over EEUC and 39% over DEBUC. Therefore, AEBUC is superior to the other two algorithms in terms of both $T_{first-dead}$, $T_{30\%-dead}$ and $T_{all-dead}$. In addition, the curve

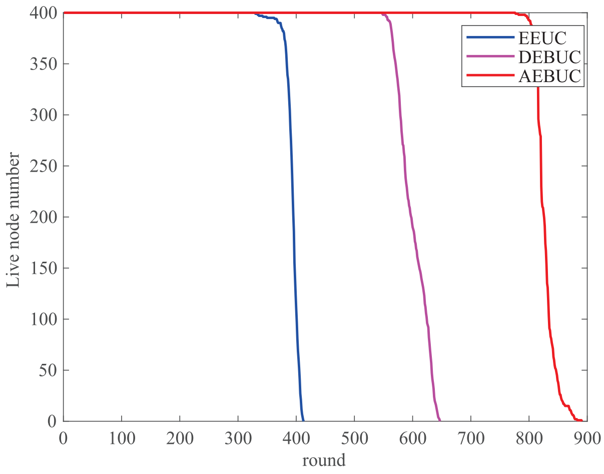


Fig. 9 Comparison of network lifetime.

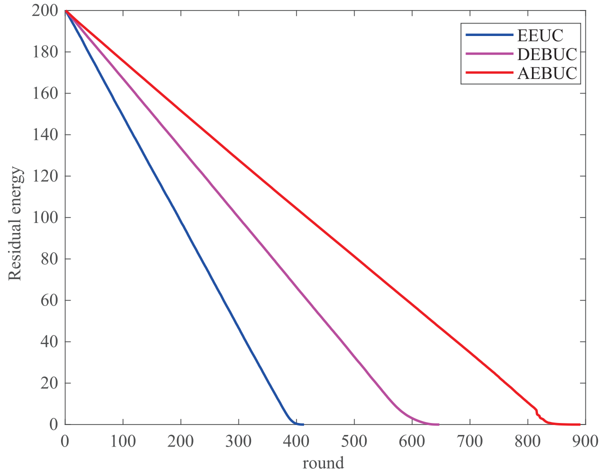


Fig. 10 Comparison of node residual energy in the network.

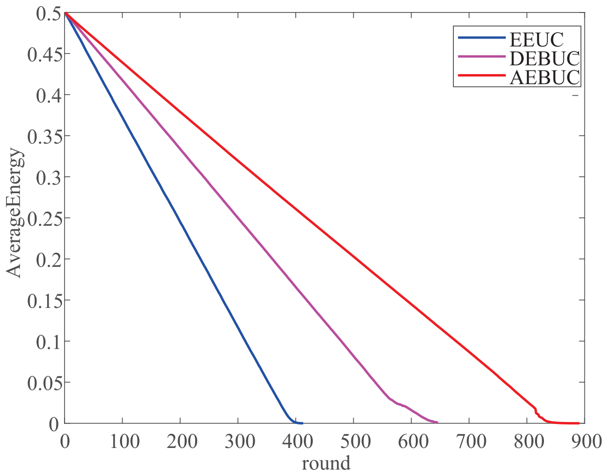


Fig. 11 Comparison of average residual energy.

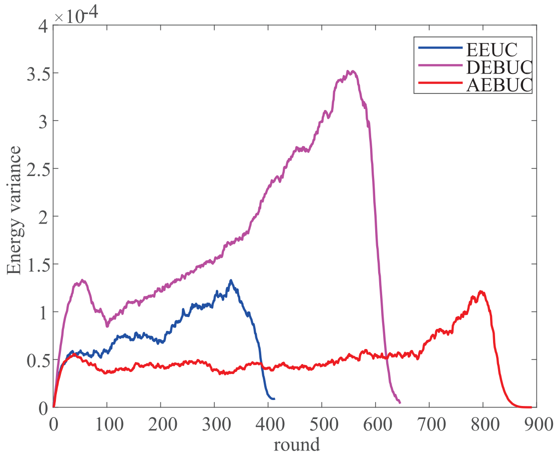


Fig. 12 Comparison of energy standard deviation.

of the AEBUC protocol has a very high slope around round 850, where most of the node energy is concentrated around round 850 energy depletion, achieving a balanced network energy consumption. Therefore, the AEBUC protocol proposed in this paper considers a variety of factors to effectively balance the energy consumption of the CH and extend the network life cycle, achieving the purpose of optimizing the network lifetime.

(3) Network energy consumption

Figure 10 shows the relationship between the remaining energy of the network over time for each round for 400 nodes. As can be seen from Fig. 10, AEBUC has more residual energy in each round than the other two protocols. The AEBUC uses the graph model-based routing representation of WSN intra-cluster communication in Sect. 2.3, which effectively reduces the energy consumption during clustering. In the inter-cluster communication routing, an optimized routing tree is generated with the CH as the node and energy efficiency as the goal, further equalising the energy consumption of the network. Taking running to 200 rounds as an example, the AEBUC has 157% higher residual energy than the EEUC and 15% higher than the DEBUC over the same period.

(4) Network energy consumption balance

Figures 11 and 12 show the average residual energy and energy variance of the AEBUC, DEBUC and EEUC during the operation of the network. Comparing the average residual energy and energy variance within the same rounds gives a better comparison of the balance of the network energy consumption. As can be seen from Figs. 11 and 12, the average energy of AEBUC is always higher than the other two protocols during the network operation, and the energy variance is obviously much smaller than DEBUC. Compared with EEUC, the maximum value of AEBUC variance is smaller than EEUC, and the maximum value of energy variance of EEUC lasts longer, while AEBUC is sharper at the maximum value, so the energy variance of AEBUC is lower than that of EEUC. In summary, with the network running time increases, the AEBUC protocol has a higher energy mean and lower variance compared to the other two protocols, verifying that the AEBUC protocol can better reduce node energy consumption and achieve network energy

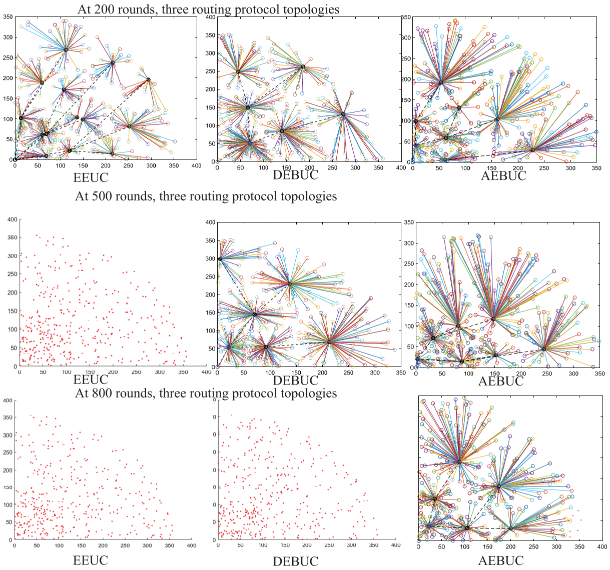


Fig. 13 Network topology comparisons.

balance in a large-scale WSN monitoring area.

(5) Network topology

Figure 13 shows a comparison of the complete network topology for the three protocols running up to 200, 500 and 800 rounds. In Fig. 13, the blue dotted line shows the transmission path between the relay CH node and the BS, and the black dotted line shows the transmission path for inter-cluster multi-hop communication. As can be seen from Fig. 13, the EEUC protocol selects only one CH as a relay node in inter-cluster multi-hop routing transmissions, so the amount of data received and transmitted by that relay CH is too large, resulting in a rapid death of the node due to high energy consumption. The DEBUC protocol has slightly smaller clusters near the BS and will have relatively more energy to forward messages from clusters further away from the BS, but the same CH is easy to be selected as a relay node by multiple CHs at the same time, consuming too much energy. The intra-cluster communication of the AEBUC protocol adopts a single-hop approach, with ordinary nodes transmitting data to CHs within clusters, and the number of clusters near the BS is large and the scale of the cluster is small; the inter-cluster communication forms a spanning tree $T = (V, E)$ with the BS as the root node, the relay CH node as the parent node and the other CH nodes as the children nodes, in line with the initial design purpose and achieving the effect of uneven clustering.

By the 200th round of the network, all sensor nodes for all three protocols are alive; by the 500th round, all nodes of EEUC has died, while DEBUC and AEBUC are not yet seen the first node die. In the mid to late stages of network running, at 600th round, the DEBUC routing protocol survived with only a few nodes located near the BS, at which point the network nodes are no longer able to cover the entire monitoring area and the monitoring data is incomplete. By the 800th round of the network, all nodes in DEBUC die due to energy exhaustion, while only a few nodes in AEBUC die and data transmission is normal. It is verified that the AEBUC routing protocol outperformed the other two routing protocols in terms of clustering and topology control.

5. Conclusion

Based on large-scale WSNs, this paper proposes an energy-efficient routing protocol for WSNs with adaptive uneven clustering. Taking the residual energy of nodes, the density of neighboring nodes and the distance to the BS as the reference amount, adaptive uneven clustering is carried out. The inter-cluster communication route is based on the residual energy and transmission distance of the relay CH node as the reference amount, using the minimum spanning tree method to select the multi-hop route with the least relay communication cost. The experimental results show that the residual energy of AEBUC is 157% higher than EEUC and 15% higher than DEBUC in the same period, which balances the energy consumption of WSN; AEBUC lifetime is 117% higher than EEUC and 39% higher than DEBUC, which significantly extends the network lifetime. Therefore, the AEBUC routing protocol proposed in this paper better solves the "energy hole" problem, generates an optimal routing tree with the goal of energy saving, balances network energy consumption, and extends the network lifetime.

In future research, to further extend the lifetime of large-scale WSNs, it is necessary to make further improvements in the node uneven distribution algorithm, and consider how to incorporate relevant models in mathematics to further research the node uneven distribution in WSNs.

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