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An Energy-Optimization Clustering Routing Protocol Based on Dynamic Hierarchical Clustering in 3D WSNs

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ABSTRACT An important issue in the three-dimensional (3D) wireless sensor networks (WSNs) is sensor energy optimization. To alleviate this issue, we introduce a new 3D spherical network structure model, and by combining the original energy consumption model to construct a new method to determine the optimal number of clusters and balance the total energy consumption. Since the different sizes of the clusters are generated by traditional hierarchical clustering, it causes unbalanced energy consumption in the network. To alleviate this problem, we adopt an improved dynamic hierarchical clustering method and implement two strategies that include the following three contributions: the introduction of the distance similarity index to get a better clustering, a double cluster head (CH) strategy to reduce the load of a cluster head in a large cluster, and a node dormancy mechanism to balance the energy consumption of the network. In addition, we also propose the optimal cluster-head function to select the CH of each cluster in each round, and the optimal cluster-head function is constructed based on the residual energy and positions of the nodes. Finally, to optimize the CH election strategy, several parameters of the optimal cluster-head function are determined according to the network structure. The simulation results show that our routing protocol is more robust compared with four other protocols, which is of great significance for the application in 3D environment monitoring.

INDEX TERMS Wireless sensor network, three-dimensional space, hierarchical routing protocol, energy optimization, lifetime.

I. INTRODUCTION

With the development of wireless network technology, wireless sensor network has become an essential part of our daily life, because these networks are being widely used in many different fields [1]. The applications include those in military monitoring, traffic control networks, underwater detection, industrial and manufacturing automation, the agricultural field and other monitoring areas [2]–[6]. However, the design of routing protocol is affected by many factors such as energy consumption, nodes deployment approach, real-time monitoring and security [7]. To alleviate the energy consumption problem of WSNs, researchers are focusing on designing energy-efficient protocols that can support various operations, and apply these energy-efficient routing protocols in 2D or 3D network models.

In recent years, many researchers have proposed various routing protocols of WSNs. These routing protocols mainly include hierarchical routing protocols, central data routing protocols, location-based routing protocols and routing protocols that provide data flow and quality of service guarantees. These networks can also be divided into homogeneous networks and heterogeneous networks according to the same and different initial energies of the sensor nodes [8]. The main hierarchical routing protocols include the low-energy adaptive cluster hierarchical (LEACH) [9],

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stable election protocol (SEP) [10], hybrid energy efficient distributed (HEED) [11], distributed energy-efficient clustering (DEEC) [12], etc.

Hierarchical routing protocols are designed by various clustering algorithm [13]–[16]. Under the clustered topology management, the sensor nodes can be divided into cluster head nodes and member nodes. To select a CH to manage its member nodes, and coordinate the monitoring work of member nodes in its cluster, meanwhile, The CH is also responsible for collecting information and merging data within its cluster and for forwarding among the clusters. Figure 1 shows the hierarchical routing protocol topology.

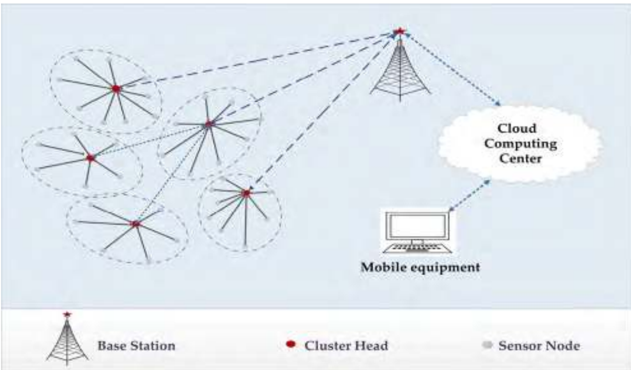

FIGURE 1. Hierarchical routing protocol topology.

The sensor nodes are arranged in the monitoring area, the member nodes are responsible for collecting the monitored information and sending these messages to the CH in a single hop. Then, the CH aggregates information and transmits the message to the base station (BS) in a single hop manner or multiple hop manner. Finally, the BS transmits the sensory information to the monitoring center through the satellite network, and the staff makes judgments based on the current environmental information [17]. In general, most researchers apply routing protocols to the applications of 2D scenarios, however, wireless sensor network protocols are mainly used in 3D scenes in real life, and energy consumption of sensor nodes in 3D environment is different in 2D environment. Nodes in 3D environment usually consume more energy than in 2D environment because of the requirement of the third dimension [18]. Therefore, an important issue in 3D wireless sensor network is sensor energy optimization. To alleviate the energy consumption issue of 3D WSN, we urgently need to design an energy optimization protocol to minimize total network energy consumption and prolong the network lifetime in 3D WSN.

In this paper, we introduce a new 3D spherical network structure model. To minimize the total energy consumption of the WSN, we combine the original energy consumption model and the 3D spherical network structure model to construct a new method of determining the optimal number of clusters. Since the different sizes of the clusters are generated by traditional routing protocols, the energy consumption of the network is unbalanced. To alleviate this problem, we adopt an improved hierarchical clustering method that includes the following three aspects: the introduction of the distance similarity index, the double cluster head strategy, and the node dormancy mechanism. In addition, this is different from the CH election in the normal hierarchical routing protocols. The optimal cluster-head function is constructed based on the residual energy and position of the node, and it is used to elect the CH of each cluster. To optimize the CH election strategy, several parameters of the optimal cluster-head function are determined according to the network structure. Finally, the influence of the communication radius of the network performance is discussed. The optimal communication radius of the network structure is determined by considering the performance of the network. To show the performance of the routing protocol proposed in this paper, we simulate the routing protocols of LEACH, SEP, HEED, DEEC and our proposed protocol in the same condition for a 3D spherical structure. The results indicate that our routing protocol outperforms the four protocols.

The rest of the paper is arranged as follows. Section II reviews the related works. Section III presents the network model and optimal cluster number calculation. Section IV presents the routing protocol with the proposed network model and assumptions. Section V presents the parameter determination and total network performance comparison. Finally, Section VI concludes this work and proposes prospects for future work.

II. RELATED WORK

One of the most important protocols proposed for a WSN is LEACH protocol [19], which introduces innovative clustering and dynamic CH selection. However, the LEACH protocol doesn't consider the residual energy of the nodes and the locations of the nodes, when transmitting information in a long distance, the energy of the nodes which are far from the CH will be exhausted in advance. Meanwhile, there are also some disadvantages in calculating the optimal cluster number and balancing the energy consumption of the network. To improve the LEACH protocol in [20], its clustering protocol was enhanced by introducing the threshold limit for CH selection and switching multiple power levels of the nodes. Compared with the original LEACH protocol, this protocol has better performance in terms of a stable phase and the network lifetime. The DEEC protocol is similarly based on LEACH protocol [21]. In [22], the HEED protocol considers the influence of the residual energy of the nodes and the total network energy of the WSN, therefore, a node with a higher residual energy have more chances to being selected as the CH, than in the LEACH protocol, which obviously improves the stability of the network and minimizes the energy consumption of the network. However, when the CH is far from the BS, its energy consumption decreases rapidly. In [23], the GSTEB protocol can reduce the energy consumption of the network better by organizing nodes with low energy power automatically through a routing tree that is created for each round. Compared with the HEED protocol and the

PEGASIS protocol, the GSTEB protocol has better network performance in reducing the energy consumption. In [24], to solve the multiple objective optimization problem of the network scale, it optimizes network configuration through a multiplication target evolution algorithm, and it performs well in the network performance optimization. Therefore, we can be informed from the related research above, the hierarchical routing protocols are almost improved based on these aspects that includes the introduction of a new network topology, the clustering algorithm, the method of CH selection, the consideration of relay nodes, inter-cluster data transmission method, and the introduction of mobile sinks. These protocols show better performance in the energy optimization, network lifetime, network throughput and network latency [25].

In recent years, the application of 3D WSNs in the target tracking, the target detection, and the security monitoring has attracted the attention of researchers in various countries. However, we know that one of the most important issues in 3D WSNs is energy optimization. Therefore, researchers need to design a reasonable sensor topology and energy efficient routing protocol to balance the total energy consumption and prolong the network lifetime [26]. In [27], it establishes different types of 3D wireless sensor network models that include optimal cluster number calculation and corresponding optimal probability analysis model. The results show that the optimal cluster number and the network energy consumption are affected by the joined noise, the network topology type and the amplified information transmission. In [28], it studies the stable CH election protocol in a 3D environment. The results show that the routing protocol applied in a 3D WSN performs worse than a 2D WSN under a same condition, therefore, the application of the protocol in a 3D WSN is more complex than a 2D WSN. Meanwhile, it also studies the application of the LEACH protocol in a 3D cube network architecture, compared with the application of the LEACH protocol in a 2D square environment, the simulation results show that the factors involved in the 3D environment are more complex than the 2D environment, the sensor nodes in the 3D environment usually consume more energy than the sensor nodes in the 2D plane environment. When the amount of the transmitted information is the same, the application of the LEACH protocol in a 3D WSN consumes more energy than the application of the LEACH protocol in a 2D WSN, and compared to the 2D WSN, the throughput of the 3D WSN is reduced by approximately 1/5 [18]. In [29], it uses a uniform network partition with equal clusters of member nodes and performs CH elections in a quasi-static manner. Compared with the condition of the non-uniform network nodes distribution, the condition of the uniform network nodes distribution has the better network stability and a network lifetime.

III. NETWORK MODEL AND OPTIONAL CLUSTER NUMBER CALCULATION

Firstly, we propose a new 3D spherical network structure and reference the energy consumption model that is proposed in [30]. Then we propose a new method to determine the optimal number of clusters based on a 3D spherical network structure.

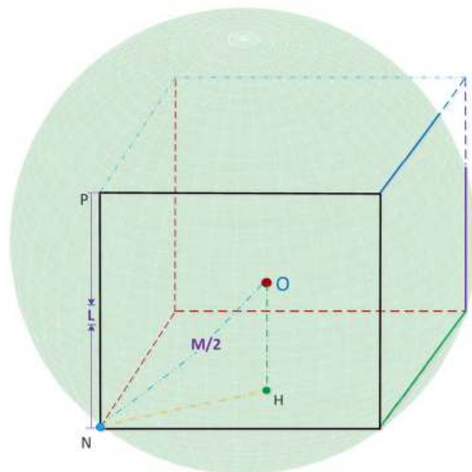

FIGURE 2. Spherical network structure.

A. THE NETWORK MODEL

Our protocol considers the network model for the following area coverage. The sensor nodes are uniformly arranged in a 3D spherical space of diameter M. The BS is located at the centre of the spherical region. To simplify the reasoning process, we use the following network structure model.

As shown in Figure 2, the radius of the sphere is M/2. A cube is embedded inside the sphere, the center of the sphere O is the center of the cube and the side of the cube is L. Here, the mathematical relationship between M and L is determined as:

$$M = \sqrt{3}L \tag{1}$$

Based on our proposed network model, the following assumptions are made for the wireless sensor network.

- The sensor nodes are fixed and each node has a unique ID number, the energy of the node is supported by a certain energy battery.
- The BS is located at the centre of the network area, and its energy can be self-replenished with powerful computing power.
- The effects of the temperature, noise and other factors which impact the sensor network are not considered.

B. ENERGY CONSUMPTION MODEL

Since the different distances of information transmission between nodes to BS, we use the free space model and the multiple path fading channel model for the different transmission distance. The energy consumption model is shown in the figure below.

As shown in Figure 3, $E_t(e,d)$ represents the energy consumption of transmitter to transmit information of e bits, and $E_r(e,d)$ represents the energy consumption of the receiver receiving the information of e bits, the distance between the

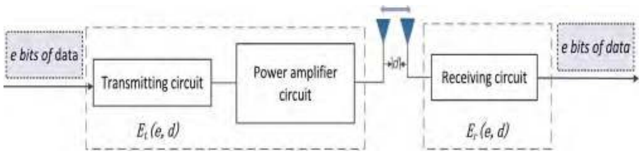

FIGURE 3. Energy consumption model.

transmitter and the receiver is denoted by d. $E_t(e,d)$ *and* $E_r(e,d)$ are calculated as equation (2) and equation (3):

$$E_t(e,d) = \begin{cases} e \times (E_{elec} + \varepsilon_{fs} d^2), & d < d_0 \\ e \times (E_{elec} + \varepsilon_{mp} d^4), & d \geq d_0 \end{cases} \quad (2)$$

$$E_r(e,d) = e * E_{elec} \quad (3)$$

In formula (2), E_{elec} is the per bit energy consumption of the transmitter or receiving circuit, and the d_0 represents the distance threshold. When $d < d_0$, we adopt the ε_{fs} to calculate $E_t(e,d)$, on the other hand, we can adopt the ε_{mp} to calculate $E_t(e,d)$. The d_0 is determined by the following formula:

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (4)$$

The energy consumption of nodes transmitting e bits information to CH can be calculated as equation (5):

$$E_{non-CH} = e \cdot E_{elec} + e \cdot \varepsilon_{fs} d_{to-CH}^2 \quad (5)$$

In formula (5), d_{to-CH} represents the distance between the member node and the CH in a cluster. We assume that the CH processes data transmission and the information size obtained is e bits in each round. The energy consumption of the CH is calculated as equation (6):

$$E_{CH} = e((\frac{n}{k} - 1) \cdot E_{elec} + \frac{n}{k} \cdot E_{DA}) + E_r(e,d) + E_t(e, d_{to-BS}) \quad (6)$$

In formula (6), n represents the number of the living nodes, and k represents the number of the divided clusters. E_{DA} represents energy consumption of the CH to process e bits data, and d_{to-BS} represents the distance between the CH and the BS.

C. OPTIMAL NUMBER OF CLUSTERS

In general, the clusters number of the network determines the total network energy consumption. A network model with the optimal cluster number can reduce the energy consumption to a certain extent, this is very important for determining the optimal clusters number of a 3D network structure to balance total network energy consumption. Therefore, to determine the optimal cluster number is very important for balancing the energy consumption of the 3D WSNs.

In this section, to determine the optimal cluster number k_{opt}. We adopt a energy consumption model and mathematical features of a 3D sphere network proposed in following statements. The distribution of the clusters in a 3D spherical network structure is shown as Figure 4.

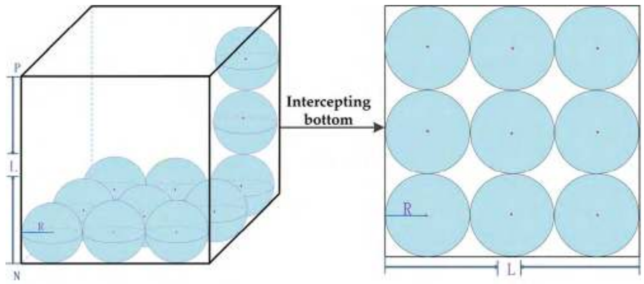

FIGURE 4. Cluster distribution in a network structure.

The left-side figure in Figure 4 is a cube model embedded in the sphere of Figure 2. The BS is at the centre of the cube, using 27 clusters as an example, and each cluster is represented by a small blue sphere. The right-side figure in Figure 4 is a bottom view of the left-side figure. We assume that the blue circles represent the clusters and the radius of a cluster is R. The diameter of the entire spherical monitoring area is M and the length of a side of the square is L. According to the basic geometric relationship, we can obtain an expression of the number of blue clusters k_1:

$$k_1 = (\frac{L}{2R})^3 = \frac{\sqrt{3}M^3}{72R^3} \quad (7)$$

The volume, V_{cir}, of the monitoring area sphere and the volume, V_{tar}, of the cube are calculated as follows:

$$V_{cir} = \frac{4}{3}\pi \cdot \left(\frac{M}{2}\right)^3 = \frac{\pi M^3}{6} \quad (8)$$

$$V_{tar} = \left(\frac{\sqrt{3}}{3}M\right)^3 = \frac{\sqrt{3}M^3}{9} \quad (9)$$

A small cluster volume, $V_{cluster}$, is defined as follows:

$$V_{cluster} = \frac{4}{3}\pi 3 = \frac{\sqrt{3}\pi M^3}{54k_1} \quad (10)$$

The total volume of the clusters, $V_{cluster\_sum}$, is defined as follows:

$$V_{cluster\_sum} = k_1 V_{cluster} = \frac{\sqrt{3}\pi M^3}{54} \quad (11)$$

It can be concluded from formula (8) and formula (11):

$$V_{cir} = 3\sqrt{3}V_{cluster\_sum} \quad (12)$$

If the network nodes can be completely divided into clusters in sphere monitoring area, the total clusters number k is $3\sqrt{3}$ times of k_1.

$$k = 3\sqrt{3}k_1 = \frac{M^3}{8R^3} \quad (13)$$

The nodes are evenly distributed in the network, so their distribution function can be obtained in equation (14):

$$g(k) = \frac{54k_1}{\sqrt{3}\pi M^3} = \frac{6k}{\pi M^3} \quad (14)$$

We can obtain the expected squared distance between the member nodes and the CH in a cluster:

$$\begin{aligned} E[d_{to-CH}^2] &= \int_0^{\pi} \sin\varphi d\varphi \int_0^{2\pi} d\theta \int_0^{R} g(k)\rho^4 d\rho \\ &= \int_0^{\pi} \sin\varphi d\varphi \int_0^{2\pi} d\theta \int_0^{R} \frac{6k}{\pi M^3}\rho^4 d\rho \\ &= \frac{24kR^5}{5M^3} \end{aligned} \tag{15}$$

According to formula (2):

$$f(d_{to-BS}) = \begin{cases} e\varepsilon_{fs} d_{to-BS}^2, & d_{to-BS} < d_0 \\ e\varepsilon_{mp} d_{to-BS}^4, & d_{to-BS} \geq d_0 \end{cases} \tag{16}$$

Therefore, we can obtain the expectation of $f(d_{to-BS})$ in formula (17):

$$\begin{aligned} E[f(d_{to-BS})] &= E[f(\rho,\theta)] \\ &= \frac{6}{\pi M^3}\int_0^{\pi} \sin\varphi \int_0^{2\pi}\int_0^{\frac{M}{2}} f(\rho,\theta)\rho^2 \, d\varphi d\rho d\theta \\ &= \frac{48}{\pi M^3}\int_0^{\frac{\pi}{2}}\int_0^{\frac{M}{2}} f(\rho,\theta)\rho^2 d\rho d\theta \\ &= \frac{24e}{M^3}\cdot\left(\int_0^{d_0} \varepsilon_{fs}\rho^4 \, d\rho + \int_{d_0}^{\frac{M}{2}} \varepsilon_{mp}\rho^6 \, d\rho\right) \\ &= \left(\frac{24\varepsilon_{fs} d_0^5}{5M^3} + \frac{3\varepsilon_{mp} M^4}{112} - \frac{24\varepsilon_{mp} d_0^7}{7M^3}\right)e \end{aligned} \tag{17}$$

For writing convenience, equation (18) can be expressed as A, and equation (17) can be expressed as equation (19):

$$A = \frac{24\varepsilon_{fs} d_0^5}{5M^3} + \frac{3\varepsilon_{mp} M^4}{112} - \frac{24\varepsilon_{mp} d_0^7}{7M^3} \tag{18}$$

$$E[f(d_{to-BS})] = A \cdot e \tag{19}$$

In each round, the average energy consumed by all nodes in a cluster is calculated as equation (20), and the total energy consumed by all clusters is calculated as equation (21).

$$\begin{aligned} E_{cluster} &= E_{CH} + (\frac{n}{k} - 1)E_{non-CH} \\ &\approx E_{CH} + \frac{n}{k}E_{non-CH} \end{aligned} \tag{20}$$

$$\begin{aligned} E_{sum} &= kE_{cluster} = kE_{CH} + nE_{non-CH} \\ &= ne(E_{elec} + E_{DA}) + kAe + neE_{elec} + ne\varepsilon_{fs}\cdot\frac{24kR^5}{5M^3} \\ &= ne(2E_{elec} + E_{DA}) + kAe + \frac{3M^2}{20k^{\frac{2}{3}}}\cdot ne\varepsilon_{fs} \end{aligned} \tag{21}$$

We can calculate the partial derivative of the E_{sum}, and let $\frac{\partial E_{sum}}{\partial k} = 0$, so we can obtain the optimal number of clusters by formula (22).

$$k_{\text{opt}} = (\frac{M^2 n\varepsilon_{fs}}{10A})^{\frac{3}{5}} \tag{22}$$

IV. THE CLUSTERING PROTOCOL

In the previous work, the optimal number of clusters, k_{opt}, is determined by the combination of the 3D spherical network structure model and the energy consumption model. Next, we propose the clustering routing protocol of this paper. The main steps of the clustering protocol are as follows:

- Step 1: Calculate the optimal cluster number, k_{opt}, using equation (22).
- Step 2: Build the required number of clusters using the hierarchical clustering algorithm.
- Step 3: A cluster head selection mechanism based on the optimal cluster-head function in each cluster is proposed. Then, we implement a dual cluster head strategy and node dormancy mechanism in the large clusters before and after the first node death to balance the energy consumption.
- Step 4: Data transmission and energy update among the network nodes according to the time slot allocation of the clustering protocol.

In each round, it is necessary to judge the residual energy of the nodes when data transmission of the network is completed, so we can perform the next iteration update. Once the node dies, we need to return to Step 1; if there is no node death, we can follow the Step 3 and Step 4. All sensor network nodes perform corresponding operations according to the time slot allocation in each round. The CH cooperates with the member nodes to fuse the perceived information, and CH transmits it to the BS through a single hop or multiple hop manner, then the staff obtains the information through the mobile device to make a decision. Respectively, the slot allocation chart of the clustering protocol and the flow chart of the protocol are shown in Figure 5 and Figure 6.

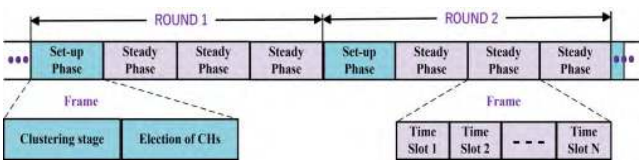

FIGURE 5. Slot allocation chart of the clustering protocol.

A. HIERARCHICAL CLUSTERING ALGORITHM

Due to the different clusters size generated by traditional routing protocols, the energy consumption of the network is unbalanced. To alleviate this problem, we adopt an improved hierarchical clustering method to cluster all the nodes until the predetermined optimal number of clusters is reached. Meanwhile, to obtain better clustering results, we propose a new two-cluster combination index called similarity.

The process of clustering is given as follows: input the sensor nodes. Each of sensor nodes constitutes a cluster at the beginning. By computing the Euclidean distance between

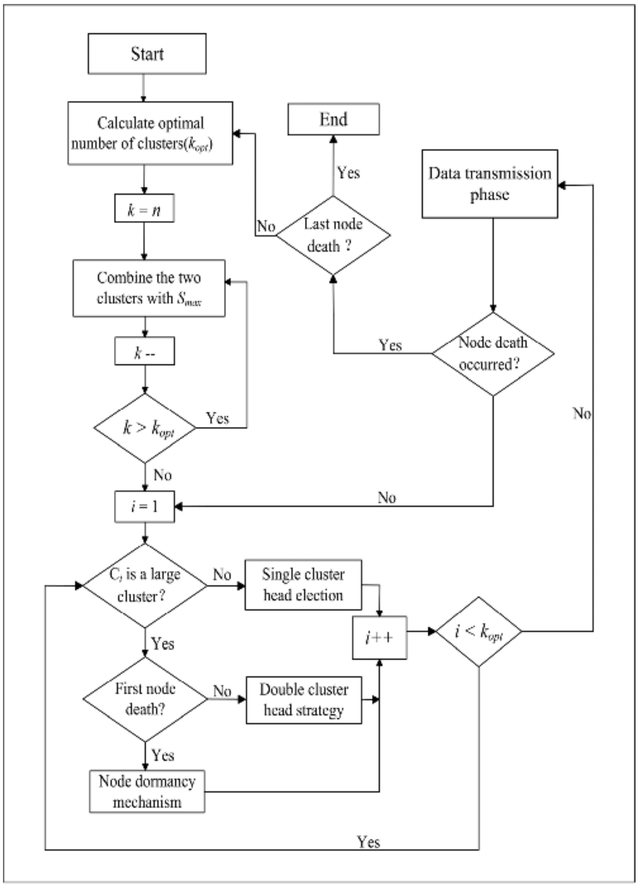

FIGURE 6. **The entire process of our routing protocol implementation.**

each pair of sample points, the two clusters with the highest similarity are continuously merged. Until the number of clusters obtained reaches the target cluster number of k_{opt} in the initial clustering phase.

The distance between the two points is calculated as follows:

$$d(C_i, C_j) = \sqrt{(C_{im} - C_{jn})^2} \tag{23}$$

C_{im} represents the m-th sample point of the i-th cluster, C_{jn} represents the n-th sample point of the j-th cluster, and the following defines the distance measure between the two clusters.

1) CLOSEST POINTS

The closest distance between two points of two clusters, $d(C_i,C_j)$, represents the distance of any two points of the two clusters, taking the minimum distance:

$$d_{\min}(C_i, C_j) = \min\{\breve{d}(C_{im}, C_{jn})|\breve{d}(C_{im}, C_{jn}) \in d(C_i, C_j)\} \tag{24}$$

2) FURTHEST POINTS

The farthest distance between two points of two clusters, taking the maximum distance:

$$d_{\max}(C_i, C_j) = \max\{\frown{d}(C_{im}, C_{jn})|\frown{d}(C_{im}, C_{jn}) \in d(C_i, C_j)\} \tag{25}$$

3) AVERAGE DISTANCE

n_1 and n_2 represent the sizes of the two clusters C_i and C_j, and the average values of the distances among all the points of the two clusters is calculated as follows:

$$d_{avg}(C_i, C_j) = \frac{1}{n_1 \cdot n_2}\sum_{n_1}\sum_{n_2} d(C_{im,} C_{jn}) \tag{26}$$

4) CLUSTER CENTRE POINT

The coordinate $(C_{i\bar{x}}, C_{i\bar{y}}, C_{i\bar{z}})$ represents the centre position of the i-th cluster; (x_{im}, y_{im}, z_{im}) is the coordinate of the m-th node in the i-th cluster; and n_i is the size of the i-th cluster, C_i, the coordinates of the centre point of a cluster are calculated as in equation (27).

$$(C_{i\bar{x}}, C_{i\bar{y}}, C_{i\bar{z}}) = (\frac{\sum\limits_{x_{im}\in C_{im}} x_{im}}{n_i}, \frac{\sum\limits_{y_{im}\in C_{im}} y_{im}}{n_i}, \frac{\sum\limits_{z_{im}\in C_{im}} z_{im}}{n_i}) \tag{27}$$

5) SIMILARITY BETWEEN TWO CLUSTERS

We introduce a new two-cluster combination index called the similarity. To achieve the predetermined optimal number of clusters, two adjacent clusters need to be merged into one cluster. Not only are the two clusters merged to meet the shortest average distance between adjacent clusters, but they also need to satisfy the maximum similarity between the two clusters.

$$S(C_i, C_j) = \frac{1}{1 + d_{avg}(C_{i,} C_j)} \tag{28}$$

In the formula (28), $S(C_i,\ C_j)$ represents the similarity between cluster C_i and cluster C_j. As the value of $S(C_i,\ C_j)$ increases, the difference between the two clusters decreases, not only can it obtain a more reasonable clustering effect and make an uneven network structure smoother, it can also effectively avoid the premature death of cluster member nodes due to the uneven transmission distance for communication.

B. CLUSTER HEAD ELECTION

In the CH election phase, the procedure of the HEED protocol is adopted. When the HEED protocol elects a cluster head, it only considers the residual energy ratio of the nodes to balance the network energy consumption, and the location of the node is not taken into account. By considering the residual energy ratio and the positional factors of the nodes, we determine the mechanism of CH election by constructing the optimal cluster-head function.

1) THE HEED PROTOCOL

Due to the randomness of the arrangement of the sensor nodes, there is an uneven distribution of the network nodes. The HEED protocol has improved the uneven network distribution, and its CH selection mainly depends on the residual energy and inter-cluster communication costs. The average minimum reach ability power (AMRP) in the cluster is used as a measure of the communication cost. It determines which cluster the node belongs to by calculating the communication cost of the node to each CH, this can result in a more reasonable network topology and balance the energy consumption of communication between nodes and CH.

Cluster formation in the HEED protocol is performed in three phases: the initial, iteration and final phases. The sensor nodes send the contention message with different initial probabilities, where CH^i_{prob} is the i-th node initialization probability, and CH^i_p represents the CH election probability of the i-th node in one round.

$$CH^i_{prob} = p_{ini} \cdot (\frac{E^i_{residual}}{E^i_{\max}}) \tag{29}$$

$$CH^i_p = \max(CH^i_{prob}, p_{\min}) \tag{30}$$

P_{ini} is the initial setting of the cluster head number ratio and P_{min} is the minimum energy ratio constant. $E^i_{residual}$ and E^i_{max} represent the residual energy and maximum energy of the nodes in the cluster in each round. The larger value of the CH^i_p is, the more likely it is that the node becomes to the CH.

In the clustering phase, it is determined whether the node joins a cluster by calculating the communication cost of joining each CH. More details can be found in [11].

2) OUR PROTOCOL

Our protocol uses the HEED protocol and improved hierarchical clustering to select the CHs in the CH election phase. The CH election mechanism not only considers whether the residual energy of the node is sufficient but also considers the location of the node. Meanwhile, we combine the network model and the energy consumption to determine the parameters for CH election in our protocol.

Usually, P_{ini} and P_{min} are constants determined by human judgement. Here, we use the optimal cluster number, k_{opt}, and the network structure to determine P_{ini} and P_{min}. N is the number of sensor nodes, and the diameter of the sphere is M. Since the radius of each cluster after clustering is different, we use the average radius, R_{clu}, of the cluster to determine the constant, P_{min}. The calculation formulas of P_{ini} and P_{min} are given below.

$$R_{clu} = \frac{M}{2} \cdot \frac{1}{\sqrt[3]{k_{opt}}} \tag{31}$$

$$P_{\min} = \frac{1}{R_{clu}} = \frac{2 \cdot \sqrt[3]{k_{opt}}}{M} \tag{32}$$

$$p_{ini} = \frac{k_{opt}}{N} \tag{33}$$

Generally, the position of the selected CH satisfies the following conditions: the CH is located near the center of the cluster area and the CH is located closer to the BS. Based on the consideration of the residual energy of the node and the position factor, we construct the optimal cluster-head function, G_p, and the CH selection needs to be re-selected at the end of each round.

$$G_P = CH^i_p + \frac{1}{ad^i_{cen} + bd^i_{to-BS}} \tag{34}$$

where d^i_{cen} represents the distance from the i-th node in the cluster to the central node of the cluster, and the d^i_{to-BS} represents the distance from the i-th node in the cluster to the BS. The weights a and b satisfy $a+b = 1$. As the value of the optimal cluster-head function, G_p, becomes larger, the easier it is for the node to be elected as the CH.

3) DETERMINATION OF a AND b

In terms of the weight coefficients, a and b, use different values for a and b, otherwise the sensor nodes have the same initial energy of 0.5 joule. The experimental results are obtained through simulation, and the simulation results use the network lifetime and the round of the first node death. We list the values of the changes in the following Table 1.

TABLE 1. Network performance changes with factors.

a	b	First node death	Network Lifetime
0.1	0.9	740	1146
0.2	0.8	812	1132
0.3	0.7	834	1123
0.4	0.6	860	1127
0.5	0.5	904	1096
0.6	0.4	916	1123
0.7	0.3	854	1134
0.8	0.2	850	1142
0.9	0.1	840	1143

First, the network lifetime and the round of the first node death in the above table are normalized. Then, the weights of the two network performance indicators are both set to 0.5, and we add the normalized values with one-to-one correspondence, which can be calculated using the following formula:

$$W_1 = 0.5\frac{death}{death_{sum}} + 0.5\frac{lifetime}{lifetime_{sum}} \tag{35}$$

When the values of a are different, the network exhibits a different performance, as shown in the following figure.

When the value of a increases from 0.1 to 0.6, the network performance gradually becomes better, when the value of a is 0.6, the network performance is the best, and finally, the network performance decreases as the value of a becomes larger. Therefore, we determine that the value of a is 0.6 and the value of b is 0.4.

C. DOUBLE CH ELECTION IN LARGE CLUSTERS

Since the size of each cluster may be different due to clustering method. For large clusters with a large number of sensor nodes, a single CH mechanism may consume most of the energy due to receiving and processing a large amount of information, this will make the energy consumption of the CH too fast, and it is difficult to transmit information to the BS due to the death of the CH in its cluster. Therefore, before the first node dies, the double CH strategy is used to divide the work to balance the energy consumption.

According to the energy consumption model introduced in Section III, n_i represents the total number of nodes in a cluster, thus, the CH energy consumption of the cluster, E_{n_i} can be calculated as follows:

$$\begin{aligned} E_{n_i} &= n_i e E_{elec} + n_i e E_{DA} + E(f(d_{to-BS})) \\ &= n_i e(E_{elec} + E_{DA}) + A \cdot e \end{aligned} \quad (36)$$

Similarly, $\bar{E}_{CH}$ is the average energy consumption of the CH, which can be calculated as follows:

$$\begin{aligned} \bar{E}_{CH} &= \frac{n}{k_{opt}} \cdot e \cdot E_{elec} + \frac{n}{k_{opt}} \cdot e \cdot E_{DA} + E[f(d_{to-BS})] \\ &= \frac{n}{k_{opt}} \cdot e(E_{elec} + E_{DA}) + A \cdot e \end{aligned} \quad (37)$$

Define the energy consumption of the CH to be greater than r times the average CH energy consumption of a large cluster.

$$E_{n_i} \geq r \cdot \bar{E}_{CH} \quad (38)$$

Therefore, the following relationships can be obtained from formulas (36) and (37), where r is the cluster head energy factor:

$$n_1 e(E_{elec} + E_{DA}) + A \cdot e \geq r(\frac{n}{k_{opt}} \cdot e(E_{elec} + E_{DA}) + A \cdot e) \quad (39)$$

The total number of member nodes, n_i, of a large cluster satisfies the following formula:

$$n_i \geq r \cdot \frac{n}{k_{opt}} + \frac{(r-1)A}{E_{elec} + E_{DA}} \quad (40)$$

1) DETERMINATION OF r

For the determination of the cluster head energy factor r, the initial energy of the sensor nodes is 0.5 joule in a homogeneous network. We also consider the situation where the double CH strategy is not implemented. The case where there is no double CH is equivalent to the value of r being 1, and r is simulated by varying the value by steps of 0.1. Since the number of the first node deaths in the simulation results is does not considerably vary, the network lifetime is used to determine the value of r. After normalizing the network lifetime value, the performance comparison chart shown in Figure 8 is obtained.

We can conclude from the comparison chart above that when the value of r is 1.6, the network lifetime value is the largest; thus, when the value of r is 1.6 the network performance is the best. More significantly, the network performance of the double CH strategy in a large cluster is significantly better than that of single CH mechanism. It also shows that implementing the double CH strategy in the large clusters can improve the network performance and balance the network energy consumption.

In the CH election phase, the number of members in each cluster is calculated first. For the small clusters, return the member sequence number of the cluster's largest cluster-head function value and elect it as the CH of the cluster. If the number of members in the cluster satisfies formula (40), the double CH election strategy is adopted. By calculating the cluster-head function value of each node, the sequence number of the largest cluster-head function value and the second largest cluster-head function value of the cluster are returned; then, they are sequentially selected as the CHs, and the CH distribution can be represented by Figure 9.

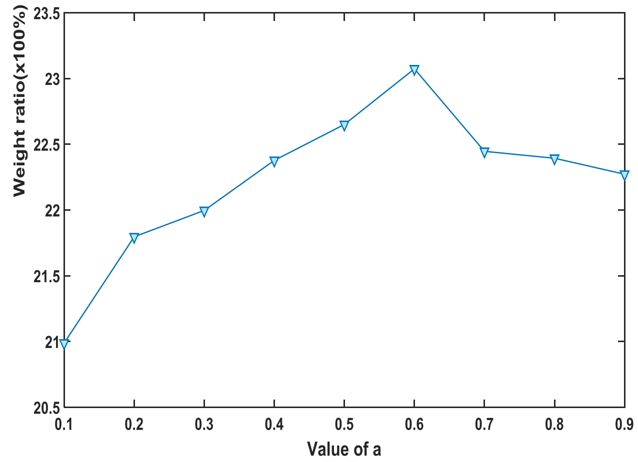

FIGURE 7. Performance changes with varying value of a.

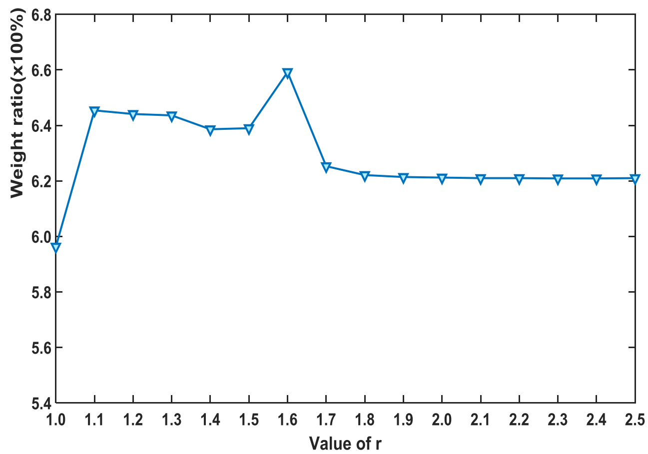

FIGURE 8. Performance changes with value of r.

The member nodes in a large cluster are responsible for collecting the environmental information that they perceive, and the information is sent to the CH by a single hop method. The secondary CH receives the information and performs data fusion from the positive CH. Finally, the information is sent to the BS, and the BS transmits it to the monitoring centre.

D. NODE DORMANCY MECHANISM

After the first node death in the network, there is a period of network instability. When the network enters an unstable phase, the energy of the cluster member nodes in a large

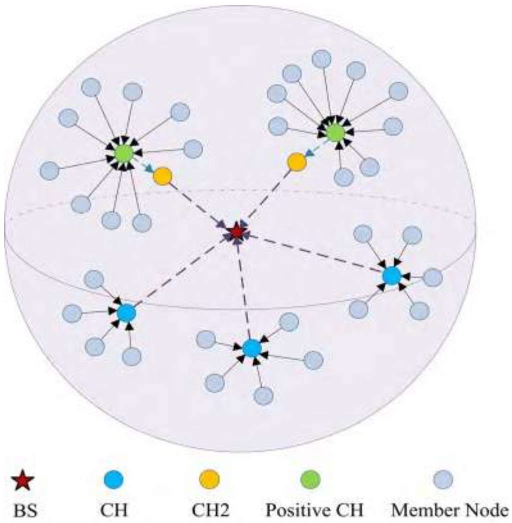

FIGURE 9. Cluster head selection distribution diagram.

cluster area is generally low, and the long-distance information transmission in the large clusters is likely to fail due to excessive energy consumption. The CH needs to receive and process a large amount of information; it also dies easily due to the excessive energy consumption. This makes the perceptual information in the large cluster will not be sent to the BS by the CH, which may miss the useful information and makes the network fall into a partially blurred state. To solve these problems, we propose a node dormancy mechanism for the large clusters after the first node death in the network.

The node dormancy mechanism proposed in this paper is mainly based on the residual energy of the member nodes and the distance between the CH and the member nodes. The dormancy factor, N_{dor}, is set for all the cluster member nodes and can be calculated as follows.

$$N_{dor}(S(i).E, d^i_{to-BS}) = \frac{S(i).E}{d^i_{to-BS}} \tag{41}$$

In the formula (41), $S(i)$. E represents the residual energy of the i-th node, and d^i_{to-BS} represents the distance of the i-th node to the BS. The smaller the energy of the node is, the smaller N_{dor} value is. As the mortality rate of the node increases, the probability of dormancy in the cluster also increases. It should be noted that it is necessary to ensure that enough nodes work properly to prevent the network system from entering a state of partial ambiguity. The following equation determines the number of dormant nodes in a large cluster.

$$N^j_{num} = \begin{cases} round(C^j_{num} - \frac{n}{k}), & C^j_{num} \geq \frac{n}{k} \\ 0, & C^j_{num} < \frac{n}{k} \end{cases} \tag{42}$$

In the formula (42), N^j_{num} represents the number of dormant nodes in the j-th cluster, and C^j_{num} represents the number of currently alive nodes in the j-th cluster. n is the total number of currently alive nodes, and k is the number of clusters currently established.

On the basis of ensuring that the network can properly monitor the environment, when some nodes in the cluster are dormant, the remaining alive nodes are working normally. When some of the alive sensor nodes consume too much energy, the value of N_{dor} is calculated in each round and arrange the value of N_{dor} from small to large. The first N^j_{num} nodes are put into a dormant state, and the remaining alive nodes are in a working state. This Strategy guarantees that those member nodes with low energy which are far from the CH are given the priority to become dormant; therefore, it can effectively reduce the load of the CH and improve the network lifetime.

V. SIMULATION RESULTS AND ANALYSIS

In this section, our protocol and four other protocols are evaluated by simulating the model with the MATLAB 2016b platform. First, we give the optimal communication radius for the network structure by considering the impact of the communication radius on the network performance. Then, we simulate our routing protocol and four other protocols to compare the differences among them with different network parameters in homogeneous networks and heterogeneous networks. We adopt the following evaluation indicators for the performance metrics: the number of CHs, the round of the first node death, network lifetime, network residual energy and throughput. When building the network model, all the wireless sensor nodes are randomly distributed in a spherical area with a radius of 100 metres, and the parameters in the simulation can be referred to in Table 2.

TABLE 2. Parameter settings.

Parameter	Value
Network area: Spherical structure (R)	100 m
Location of the BS	(0, 0, 0)
Number of the nodes (N)	150
E_{elec}	50 nJ/bit
E_{DA}	5 nJ/bit/message
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
a	0.6
b	0.4
r	1.6
Size of the data packet	4000
Initial energy	0.3~0.7 J

Firstly, we give the distribution of the sensor nodes in a spherical network structure with a radius of 100 metres. The sensor nodes are uniformly placed, and the small blue balls represent the sensor nodes. The BS is located in the network centre, and the red pentagram represents the BS. Figure 10 shows the distribution of the sensor nodes in a spherical network structure.

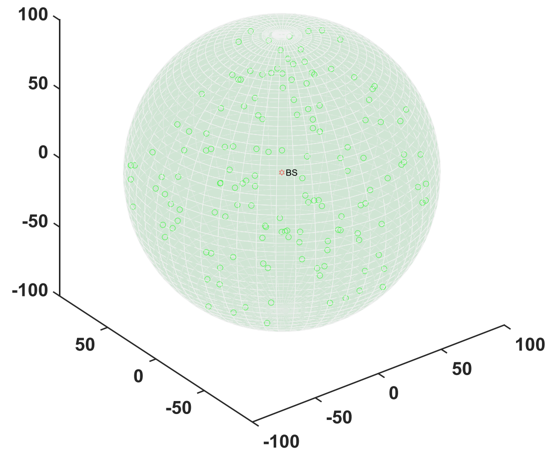

FIGURE 10. **Network sensor node distribution in a spherical network.**

A. DETERMINATION OF THE COMMUNICATION RADIUS

We know that the communication between nodes and nodes is affected by the distance from the energy consumption model proposed in Section III. Different communication radii will result in different levels of energy consumption for node communication, and it is necessary to determine the optimal communication radius for our network model.

When performing the simulation, the initial energy of the nodes is 0.5 J in the homogeneous network. To evaluate the impact of the communication radius on the network performance, we use the network residual energy, the network throughput, and the number of rounds at the first node death. The performance comparison diagrams are given as follows.

As shown in Figure 11, when the incremental step of the communication radius is set to 5, as the communication radius varies from 40 to 90, the other parameters remain the same.

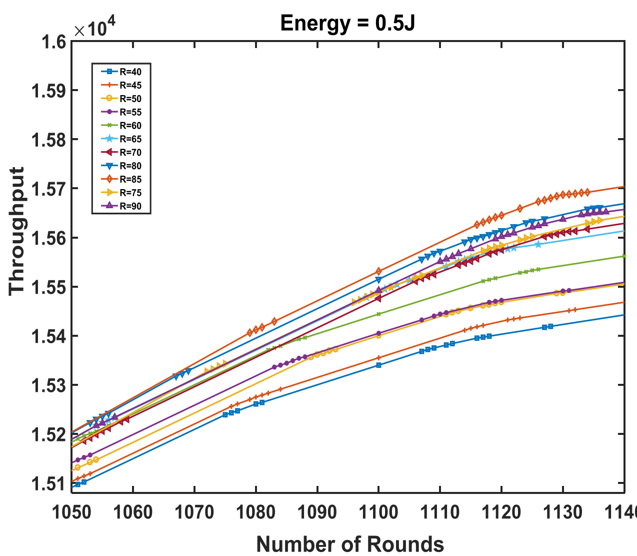

FIGURE 11. **The throughput varies with the number of rounds.**

When the communication radius is less than 85, the network throughput increases as the communication radius increases. When the communication radius is greater than 85, the network throughput decreases as the communication radius increases. This suggests that the maximum network throughput corresponds to a communication radius of 85.

As shown in Figure 12, to analyse the simulation results in more detail, the variation in the residual energy of the network after 1000 rounds is considered. When the communication radius is less than 85, the residual energy value of the network increases as the communication radius increases over 1000 rounds. When the communication radius is greater than 85, the network residual energy decreases as the communication radius increases over 1000 rounds. Therefore, the communication radius corresponding to the maximum network energy at 1000 rounds is 85.

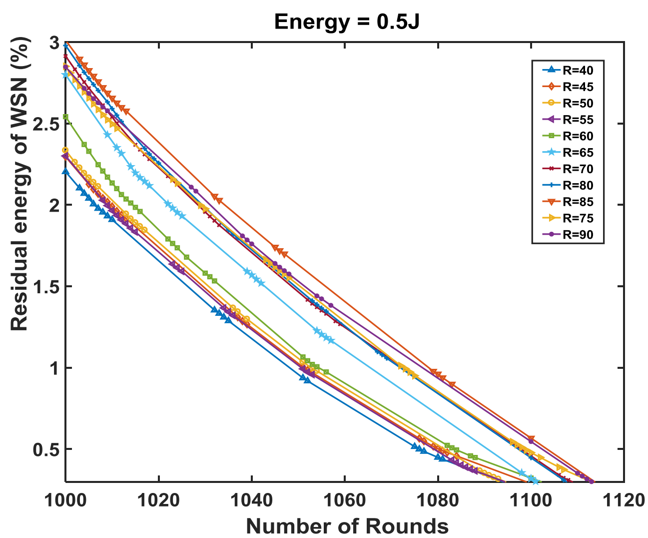

FIGURE 12. **The residual energy varies with the number of rounds.**

Since the number of rounds for the first node death is not much different, it is not listed here. From the results, we can conclude that the maximum communication radius of the residual energy is 75; meanwhile, the residual energy is very small when the communication radius is 75 or 85. Therefore, considering all the factors, the communication radius with the best network performance is 85.

B. COMPARISON OF THE NUMBER OF CHs

In this section, we discuss the number of CHs and give the distribution of the nodes in the network. Here, we compare our protocol with the LEACH protocol in the change of the number of the CHs in a homogeneous network. The comparison of the number of the CHs is shown in Figure 13.

The main3D protocol is the routing protocol proposed in this paper, and the number of CHs is the same as the theoretical value given in equation (22). Others3D protocol represents a routing protocol that randomly elect CHs using a threshold. It can seen from the results that the CH selection mechanism used in the network model, and energy

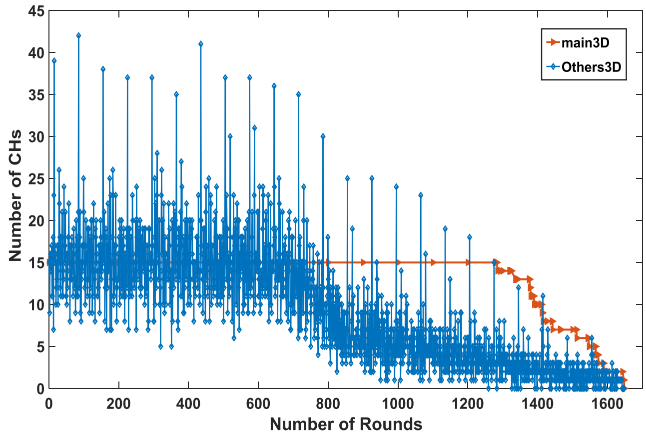

FIGURE 13. The number of CHs varies with the number of rounds.

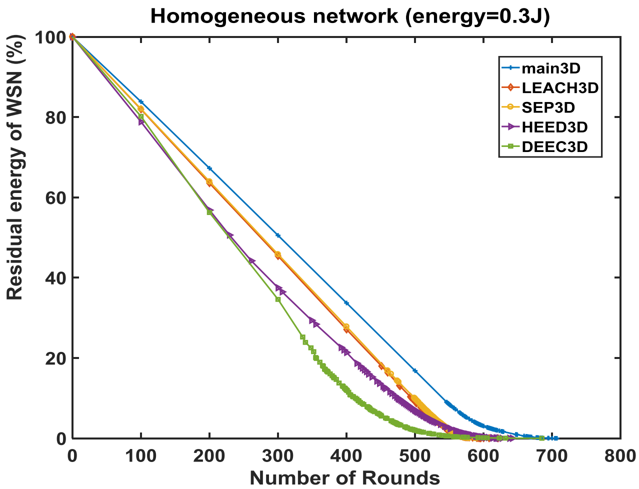

FIGURE 14. The residual energy varies with the number of rounds (0.3J).

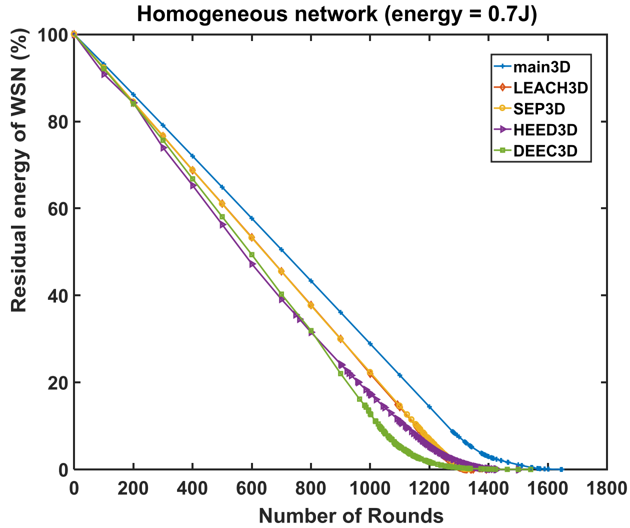

FIGURE 15. The residual energy varies with the number of rounds (0.7J).

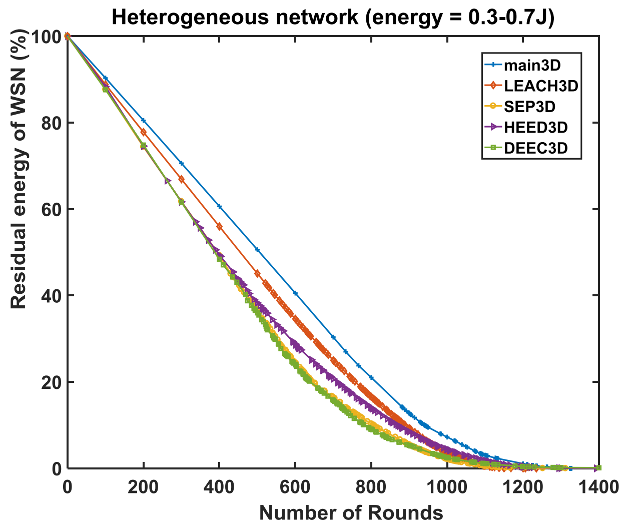

FIGURE 16. The residual energy varies with the number of rounds.

consumption models is more reasonable, which can reduce the energy consumption required for CH election and prolong the network lifetime to some degree.

Due to the routing protocols such as LEACH protocol, HEED protocol and DEEC protocol, the CH selection is determined by comparing a set threshold. This makes the number of cluster heads selected by the threshold change randomly in each round, which consumes unnecessary energy in the CH election process, which is not conducive to balancing the residual energy of the network. According to the 3D spherical network structure proposed in this paper, referring to the energy consumption model, the optimal number of clusters is determined theoretically, which makes our CH election mechanism more reasonable.

C. COMPARISON OF THE ENERGY CONSUMPTION

In this section, we discuss the network energy consumption, which refers to network residual energy of the WSN computed after each round. We give the nodes an initial energy of 0.3∼0.7J in a homogeneous network or a heterogeneous network. The main3D protocol represents our routing protocol. The SEP3D, HEED3D, LEACH3D, and DEEC3D models represent these four protocols: SEP protocol, HEED protocol, LEACH protocol, and DEEC protocol, respectively, which are simulated in our 3D spherical network.

It can be concluded from the above three comparison charts that our routing protocol has more residual energy than the other four protocols at any end of a round. We propose a new optimal number of clusters method based on the energy consumption model and the 3D network model. In the election of the CH, the residual energy of the node and the positional influence of the node are introduced. At the beginning of each round, we select the CHs based on the residual energy and positions of the nodes. Meanwhile, we carry out the double CH strategy before the first node death and the node dormancy mechanism after the first node death. Compared to the other four protocols, this protocol has better performance in balancing the network energy consumption.

D. COMPARISON OF THE NETWORK LIFETIME

The network lifetime is defined by the number of alive nodes at each round. In this section, we discuss the network lifetime in homogeneous and heterogeneous networks, and the simulation results are shown as follows.

As shown in Figures 17 and 18, our protocol obtains the longest network lifetime when the given initial energy of a node is the same in a homogeneous network. The longest lifetimes for the HEED3D and DEEC3D protocols are less than that of our protocol, and the network lifetime between them is not much different; the SEP3D protocol and LEACH3D protocol have poor lifetime performance. The SEP3D protocol considers the effects of the initial energy on the basis of the LEACH3D protocol. However, the difference between the SEP3D protocol and the LEACH3D protocol is very small in a homogeneous network. As the number of rounds increases, the advantages of the HEED3D and DEEC3D protocols are gradually reflected. Compared with the protocol with the second largest network lifetime, our routing protocol has prolonged the network lifetime by 5.62% and 9.65%.

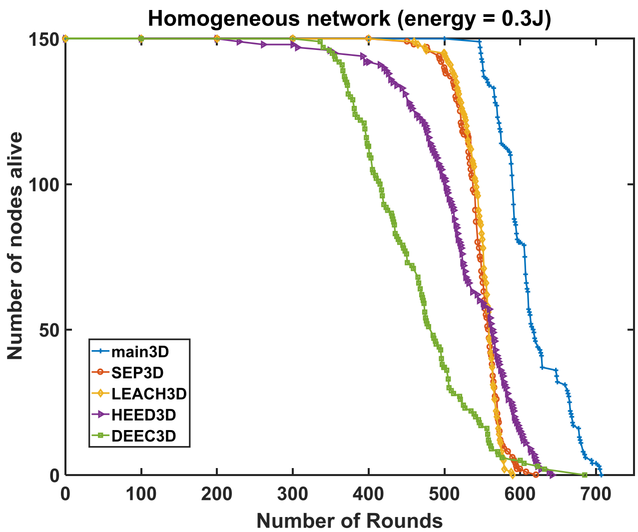

FIGURE 17. Number of alive nodes varies with number of rounds (0.3J).

As shown in Figure 19, in a heterogeneous network, the HEED3D protocol compares with the LEACH3D and SEP3D protocols, and the number of alive nodes in the HEED3D protocol is smaller in the early phase. The HEED3D protocol caused many nodes with a higher initial energy to die in the early phase, so that there are more nodes with less initial energy in the network. The HEED3D protocol considers the effect of the residual energy ratio, and the DEEC3D protocol considers the initial energy and residual energy of the nodes in the later phase. The energy distribution of such nodes in the HEED3D protocol and the DEEC3D protocol is more balanced, which can maintain a longer network lifetime.

It can be concluded from Figure 19 that the HEED3D protocol and DEEC3D protocol have a larger network lifetime than the LEACH3D and the SEP3D protocols in heterogeneous networks. Compared with them, our protocol still maintains alive 78 nodes in 1000 rounds, while the LEACH3D, SEP3D, DEEC3D and HEED3D protocols only have 43, 30, 28 and 43 alive nodes. Respectively, this shows that our protocol can carry out more rounds of network communication and prolong the network lifetime of a homogeneous or heterogeneous network.

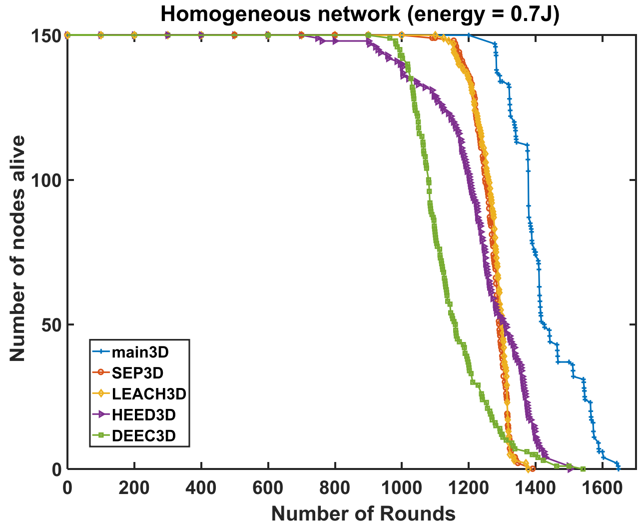

FIGURE 18. Number of alive nodes varies with number of rounds (0.7J).

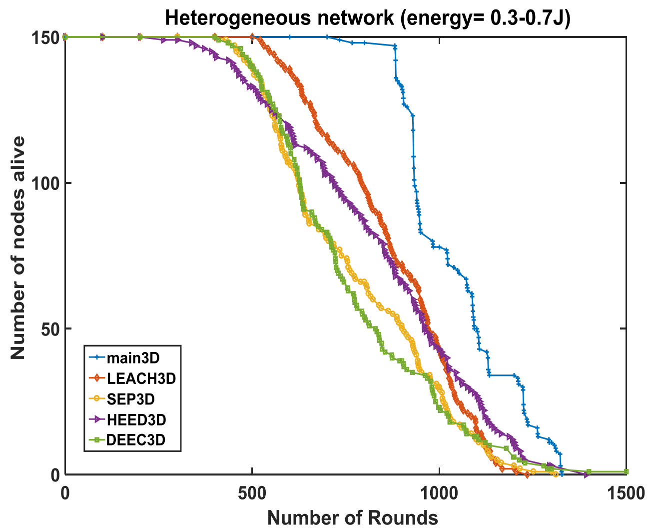

FIGURE 19. Number of alive nodes varies with number of rounds.

E. COMPARISON OF THE NETWORK THROUGHPUT

The network throughput refers to the number of packets in the network that are ultimately sent to the BS. Each cluster member node sends its own sensed information to the CH in the form of a packet, the CH fuses this information with its own sensed information and finally sends the information to the BS in the form of a packet. We discuss the performance comparison between our protocol and other protocols in network throughput, and the simulation results are shown in the following figures.

From the above simulation results, it can be concluded that our protocol has a significant improvement in network throughput compared to that of the other protocols, whether in a homogeneous or heterogeneous network. As shown in Figure 20 and Figure 21 in the homogeneous network, the network throughput of this protocol increases by 58.39% and 53.06%, respectively, compared to the HEED3D protocol with the second largest network throughput. As shown in Figure 22, in heterogeneous networks, the DEEC3D protocol has the second largest network throughput. Compared with the DEEC3D protocol, the network throughput of our protocol increased by 22.6%.

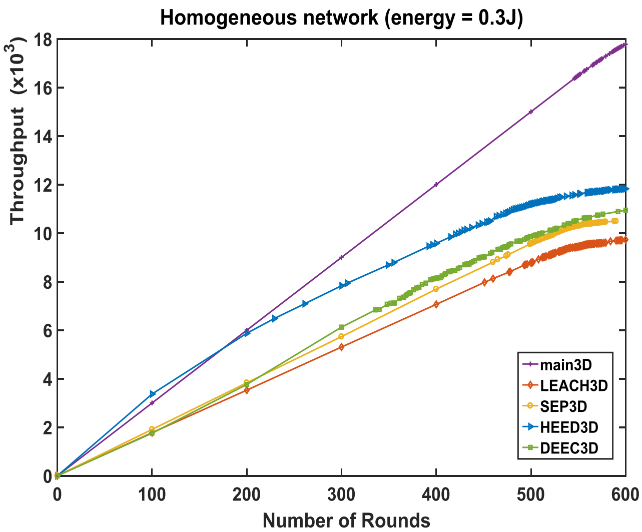

FIGURE 20. Network throughput varies with number of rounds (0.3J).

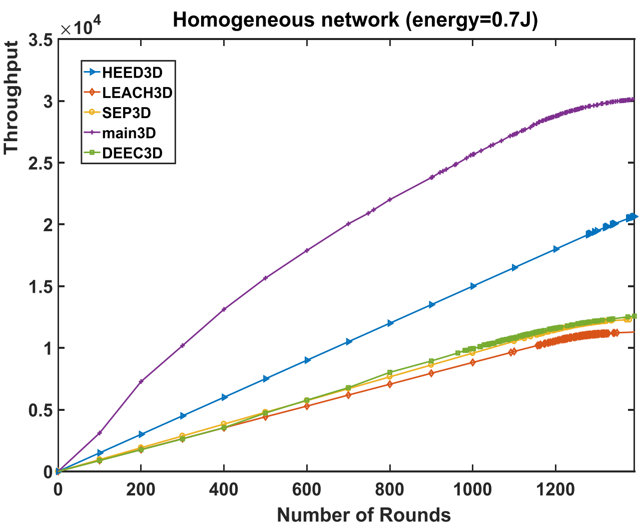

FIGURE 21. Network throughput varies with number of rounds (0.7J).

F. COMPARISON OF THE FIRST NODE DEATH

The round of the first node death is an important parameter to measure the network performance. In a wireless sensor network, the network is in a stable phase before the death of the first node. When the first node dies, the network enters an unstable phase, and the first node death indicates that the network performance will begin to decline. The comparison of the number of rounds before the first node death in homogeneous networks and heterogeneous networks is given below.

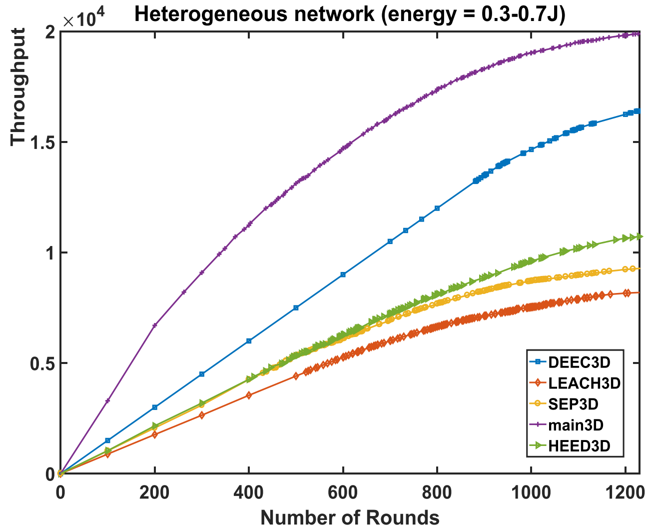

FIGURE 22. Network throughput varies with number of rounds (0.3-0.7J).

As shown in Figure 23 and Figure 24, our protocol has the maximum number of rounds before the first node dies, whether in a homogeneous network or a heterogeneous network. As shown in Figure 23, in a homogeneous network, as the initial energy of a given node increases, the number of rounds before the death of the first node increases. This demonstrates that the initial energy of the node determines the network lifetime. As shown in Figure 24, in a heterogeneous network, as the range of the initial energy of the node increases, the performance of the network is not necessarily better, and it depends on the size of the initial energy of the node. Due to the large energy gap among the sensor nodes,

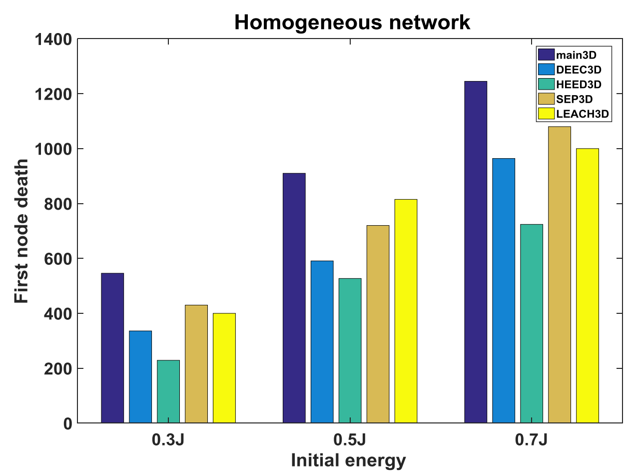

FIGURE 23. The round of the first node death (Homogeneous Network).

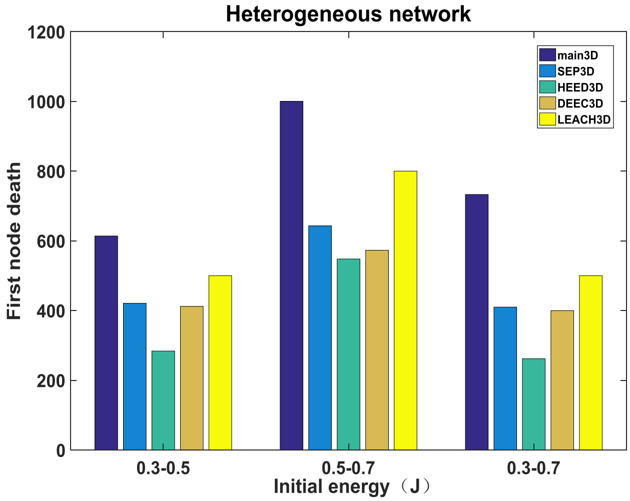

FIGURE 24. **The round of the first node death (Heterogeneous Network).**

the LEACH3D and SEP3D protocols only consider the initial energy of the node, which will cause the high energy nodes to perform multiple rounds of updating. In the case of nodes with less energy, there is still a higher probability of being selected as the CH, which increases the rate of death of the node, leading to an earlier death of the first node. The HEED3D and DEEC3D protocols comprehensively analyse the initial energy and residual energy of the node, this can ensure that the that the probability of nodes with higher initial energy being elected as the CH after multiple rounds of data updating is lowered, so that other nodes with higher residual energy have a higher probability of being elected as the CH. None of these four protocols considers the locations of the nodes, which results in more energy usage, and nodes in more remote locations are selected as the CH, causing an unnecessary waste of energy. Our protocol considers the node's energy, while considering the node's positional influence in each round ensures that the CH node has more energy and a better position. We implement the double CH strategy before the first node death, thus, our CH selection strategy can effectively balance the energy consumption of the network and can prolong the round of the first node death.

VI. CONCLUSION

This paper considers the clustering routing protocol application of WSN in 3D spherical network, and we propose a new energy-optimization routing protocol based on dynamic hierarchical clustering in 3D WSN. To optimize the network energy consumption and prolong network lifetime. The main innovations we have proposed are as follows: the optimal cluster number based on a new 3D spherical network; a novel merge index between two clusters called similarity; an optimal cluster-head election function based on the consideration of the residual energy, location of nodes, and mathematical characteristics of network; the dual CH strategy and node dormancy mechanism are implemented before and after the first node death. Respectively, in each round, it is necessary to re-elect the CHs and update the information transmission.

From the simulation results in Section V, the results of simulation experiments suggest that our routing protocol shows better performance in network lifetime, throughput, and network energy consumption compared with other protocols, whether in homogeneous networks or heterogeneous networks. Figure 13 suggests that the starting number of CHs in our protocol accounts for approximately 10% of the total number of sensor nodes, which is very close to the CH election probability of other protocols. The experimental values of the optimal number of clusters selected dynamically are consistent with the theoretical calculations given. This shows that the optimal cluster number and CH election strategy are reasonable, therefore our protocol is suitable for the application of monitoring in 3D spherical structure, and it is of great significance for 3D environment monitoring.

We certainly have some shortcomings in our protocol and some issues to be solved will be studied in our future academic work.

If the data dimension is large, the number of samples with similar distances will increase in the clustering process, it will become impossible to compare the similarities between them and the sample points cannot be clustered well. This issue will cause the computational complexity of the algorithm to increase, which will increase the network data transmission and reception delays. In future work, we can not only focus on the performance of the protocol but also consider the real-time operation of the protocol and the complexity of the protocol algorithm.

In addition, we do not consider that a transmission failure may occur due to the uncertainty of the factors in a natural environment in the information transmission process, or that there may be noise and other factors in the actual 3D environment. In the future work, the influence of noise can be considered and a noise probability model can be introduced for a 3D environment. We will also delve into the impact of the number and distribution of the relay nodes on the lifetime of a 3D WSN, and explore how to extend the current wireless sensor network applications to various 3D environment monitoring scenarios.

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