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RESEARCH ARTICLE

Research on the Routing Method of Swarm Network Based on Moth Search Link Distance and Residual Energy Weights

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ABSTRACT Routing method is a key technology for swarm communication. In order to reduce the node energy consumption in large-scale swarm communication, a routing method based on moth search link distance and residual energy is proposed. First, the swarm network is divided into sub-cluster networks by filtering of cluster head nodes. The node with more residual energy is used as cluster head to forward data signals from other nodes. The link between cluster head and edge nodes is established by relaying the signals from the nodes. The routing function of the link is established by calculating the distance and residual energy weight of the nodes. During cluster head broadcast communication, a modified moth-based search algorithm is applied to solve the combined weights of the routes. The optimal solution of the function constitutes the best route within the subcluster. Simulation results show that the proposed method meets the communication requirements, while the performance of the proposed method is higher than other mainstream algorithms by comparing the magnitude of three metrics: network coverage, residual energy and BER. The proposed routing method reduces the energy consumption of multi-node cluster network communication. The method achieves routing for large-scale cluster communication.

INDEX TERMS Swarm network, routing method, link length, node residual energy, moth search algorithm.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are widely used in industrial and agricultural fields because of their low cost and simple operation. Due to the limited communication range of a single UAV, UAV swarm communication has become a hot research topic at present [1], [2]. With the increase of the number of communication nodes, the energy consumption of large-scale unmanned communication has been paid more attention by scholars. A reasonable routing method can reduce the energy consumption of the network and enhance the stability of communication [3].

In recent years, cluster communication has become an effective method to reduce network energy consumption [4]. In 2020, Cao D et al. proposed the network architecture of multi-node cluster communication, the model of multi-node forwarding communication was proposed, and the expression of relay forwarding node was established [5]. Martinaa M et al. improved the algorithm efficiency in UAV energy transmission, and a routing algorithm for cluster communication based on energy sensing was proposed [6]. In 2021, an energy-efficient and novel populated cluster aware routing protocol was proposed by Huang et al [7]. The algorithm generates several network groups. According to the network size, the nodes with high energy are defined as network cluster heads. But with the constant change of node information, cluster head selection needs to consume a lot of energy. Later, Chen et al. proposed a cluster communication protocol for cooperative communication [8]. Network communication uses polling to determine cluster heads to complete data transmission. The energy consumption of the network is reduced due to the sleep of other nodes. Subsequently, Cao et al. designed a route selection method with unbalanced residual energy [9]. Packet nodes that transmit more data get higher

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energy. Limited energy is used for data transmission. But the calculation of dynamic energy distribution coefficient consumes more energy. With the rise of machine learning technology, Bao et al. proposed a route selection method simulating water wave jumping to solve the energy allocation problem of multi-hop networks [10]. The nodes with more signal transmission can obtain energy dynamically and the network communication time is prolonged. Ngangbam et al. designed a routing decision based on dynamic adjustment of cluster head residual energy [11]. Cluster-head nodes are connected to the network according to energy residual values. Although cluster communication can reduce network consumption, the energy of computing dynamic node information is also increasing. The calculation method of cluster head node needs to be improved.

The optimal relay node selection method is constantly updated due to the increase of network communication nodes. In 2020, Suriya Praba et al. designed a multi-node average signal-to-noise ratio algorithm to determine the optimal relay node [12]. The optimal relay node selection function is constructed through the signal-to-noise ratio parameter of the link signal, and a KKT optimal solution calculation method is applied to calculate the optimal solution of the function. Multiple intermediary nodes are selected by solving the optimal solution of the function several times, and trunk links are constructed by linking multiple optimal trunk nodes. In the same year, a link construction method based on harmony search algorithm was proposed by Agrawal et al. [13]. The method quickly calculates the routing function of the link due to the simplification of the calculation process. However, the iteration times of the algorithm increase due to the frequent change of node position. In order to solve the error problem caused by node movement in communication links, Xue et al. proposed an optimal routing link selection method based on the maximum-min principle in 2020 [14]. The maximum channel gain of the segmented link is calculated and the maximum channel capacity of the entire link is determined by filtering the minimum segmented link channel capacity through the information collected by the node. The method determines the maximum channel transmission capacity of the communication link and the process of solving the link capacity is simplified due to data preprocessing. In the same year, Nagendranth et al. designed a link distance shortest ratio selection method [15]. Due to the constant change of communication node location, the modification method was improved by Ren et al. A comprehensive comparison method of relay link distances is proposed to reduce channel competition conflicts [16]. However, in multi-link network communication, the influence of multi-hop link length is not considered. In 2022, Lin introduced AI technology into the selection of network relay nodes and designed a relay selection method based on AI algorithm to solve average channel information [17]. The algorithm calculates the channel information of all nodes through the global search method, and the maximum node and link channel information are selected through the competitive algorithm, but the complexity of the algorithm is increased due to the use of AI algorithm. By comparing the above algorithms, it is found that the change of node information in the cluster network is the difficulty in the selection of relay nodes. The complexity of node and link information is the main reason for the energy consumption of the algorithm. Therefore, the calculation of nodes in the cluster network needs to reduce the energy consumption. Table 1 shows the comparison of the existing routing protocols, regarding the energy constrained routing protocols are valued because of the extended network survival time.

TABLE 1. Comparison of classical routing algorithms.

Classification	Research Content	Protocol
Mainstream algorithms	The links are compared according to their channel gain and the link with the highest channel gain is filtered	DSDV, OLSR, MPEAPLSR
Distance of link	Selection is based on the length of the link, with the smallest link length being defined as the best route.	DSDV, DSDV-R
Residual energy of the node	The best route is determined by connecting the high nodes with residual energy	EEMP-AODV
Link angle	Connect nodes with angles less than the threshold before and after the link to form the best route	LD-AODV
Random Routing	Random route selection according to the existing K-connectivity of the node	DSR, AC-DSR
Minimum interruption probability	Select the link with the minimum outage probability defined as the best route	MPEAPLSR

To reduce the energy consumption of nodes in communication, A routing algorithm based on moth search link distance and energy weights is proposed. The network is first divided into ask cluster groupings, the links between cluster heads and nodes are established, and the routing function is designed by calculating the node distances and the remaining energy values. The improved moth search algorithm solves the optimal solution of the function. The performance of the improved algorithm is found to be higher than other mainstream algorithms by comparing time and capacity parameters through experimental comparison [18], [19], [20], [21]. The proposed algorithm reduces the energy consumption of routing and the algorithm is more suitable for large-scale UAV swarm network communication.

II. ROUTING THEORY OF UAV CLUSTER COMMUNICATION

A. CLUSTER HEAD SELECTION IN CLUSTER COMMUNICATION

The UAV cluster network includes relay and forwarding UAVs, cluster head UAVs and detection UAVs. Three kinds of UAVs with different functions constitute a cluster. The cluster heads transmit information between clusters and control the selection of routes within the cluster [22]. Figure 1 is a

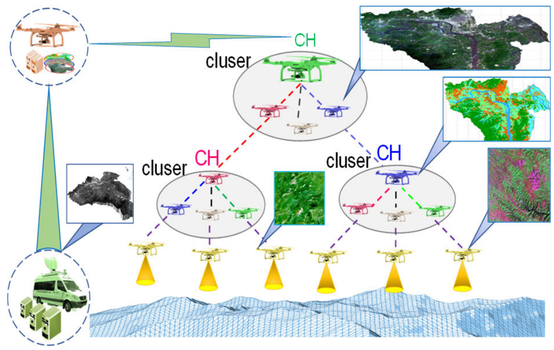


FIGURE 1. Schematic diagram of multi-route communication process in UAV cluster network.

schematic diagram of the communication process of the UAV cluster. The cluster-head UAV collects the data of the detection UAV, and the low-level cluster forwards the information to the high-level cluster.

The cluster head (CH) is a node with high residual energy. The cluster head transmits data inside the cluster outwards, while other nodes do not. Cluster heads are determined through node residual energy competition. After the broadcast communication between nodes, the remaining information of nodes is recorded, the result of node competition is calculated according to formula (1-5). When the maximum remaining energy node is determined, the marking information of cluster head node is notified to other nodes, and the competition process is terminated.

$$E_{ch} = \max(E_{ci}) \tag{1}$$
$$E_{ci} = E_{oi} - E_{ti} - E_{ri} \tag{2}$$
$$E_{ti} = E_{rc} \times m + E_a \times m \times d^2 \tag{3}$$
$$E_{ri} = E_{rc} \times m \tag{4}$$

In the formula, E_{ch} represents the remaining energy of the cluster head, E_{ci} represents the remaining energy of the network node, E_{oi} is the original energy of the node, E_{ti} is the energy consumed by the node to send 1 bit of information, E_{ri} is the energy consumed by the node to receive 1 bit of information, E_{rc} represents the energy consumed by coding, E_a represents the energy consumed by the amplifier, m represents the number of bytes sent by the node, and d represents the node the effective distance of the amplifier. The coefficient i represents the i-th node and n represents the number of communicating nodes, $i = 1, 2, 3, \ldots, n$.

B. CLUSTER COMMUNICATION TRUNK NODE SELECTION

The relay node is determined by comparing link distance and residual energy values. A comprehensive weight value is established by calculating the distance between nodes and the residual energy value. The distance parameter between the borrowing points is calculated through the position information, and the residual energy is calculated through the above formula [23], [24].

$$R_i = \max R(w_i) \tag{5}$$

$$w_i = \alpha \times E_{ci} + \beta \times \frac{\lambda}{d_i} \tag{6}$$

$$d_i = \sqrt[2]{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2} \tag{7}$$

In the equation, R_i represents the best relay node, $R(w_i)$ represents the combined weight value of energy and distance of the pass node, E_{ci} represents the remaining energy of the network node, d_i represents the distance from the i-th node to the $i + 1$st node, and λ represents the distance reconciliation parameter with a value of 0.01 times the communication period. α and β represent the weight parameters of energy and distance, respectively, and have $\alpha + \beta = 1$, x_i and y_i denote the spatial location coordinates of the nodes, $i = 1, 2, 3, \ldots, n$. The j link contains $m + 1$ nodes, and the calculation formula of the comparison function L of routing links is determined by combining the weight coefficient of multi-segment links.

$$L(j) = \sum_{j=1}^{m} R_j \tag{8}$$

In the formula, $L(j)$ denotes the route of the jth link, R_j denotes the link composed of j relays, $j = 1, 2, 3, \ldots, m$.

The amount of information transmitted by each route is determined by the mutual information capacity between compute nodes. The calculation process of information capacity has the following extrapolation to process solving [25], [26].

$$I = \frac{L}{n+1}\log\left[1 + E_s |h_{sd}|^2 \,\mathrm{SNR} + \sum_{i=1}^{n} f\left(E_s |h_{sr}|^2 \,\mathrm{SNR}, E_r |h_{rd}|^2 \,\mathrm{SNR}\right)\right]$$
$$f(x, y) = \frac{xy}{x + y + 1}. \tag{9}$$

In the equation, I denote the link mutual information quantity, s denotes the source node, r denotes the relay node, d denotes the destination node, h denotes the channel gain, SNR is the signal-to-noise ratio, and f is a functional calculation formula. To simplify the process of solving the above equation, an improvement $\Gamma = K \cdot S \cdot d^{-\beta} \cdot \mathrm{SNR}$ is introduced by referring to the following equation. K represents the loss parameter of link, d represents the distance of the link and S represents the link attenuation parameter.

$$I = \frac{L}{n+1}\log\left[1 + E_s |a_{sd}|^2 \Gamma_{sd} + \sum_{i=1}^{n} f\left(E_s |a_{sr}|^2 \Gamma_{sr}, E_r |a_{rd}|^2 \Gamma_{rd}\right)\right] \tag{10}$$

The link minimum outage probability function in UAVs communication is constructed by link mutual information expressions.

$$P_{out} = P_r[I < R] = P_r\left[E_s |a_{sd}|^2 \Gamma_{sd} + \sum_{i=1}^{n} f\left(E_s |a_{sr}|^2 \Gamma_{sr}, E_r |a_{rd}|^2 \Gamma_{rd}\right)\right.$$

$$< \left(2^{(n+1)R} - 1\right) \Bigg] = C(n) \frac{1}{E_s \Gamma_{sd} \sigma_{sd}^2} \prod_{i=1}^{n} \left(\frac{1}{E_s \Gamma_{sd} \sigma_{si}^2} + \frac{1}{E_i \Gamma_{rd} \sigma_{id}^2} \right) \tag{11}$$

Here, $C(n) = \left(2^{(n+1)R} - 1\right)^{n+1} / (n+1)!$

With the energy consumption of UAV, the energy distribution coefficients of the communication nodes are established to control the use of energy. The energy coefficients within the sub-cluster are as follows.

$$\sum_{i=1}^{n} \gamma_i = 1 \tag{12}$$

As energy constraints are introduced, the interrupt function is re-updated.

$$P_{out} = C(n) \frac{1}{\gamma_0 \sigma_{sd}^2 \Gamma_{sd} (E_t)^{n+1}} \prod_{i=1}^{n} \left(\frac{1}{\gamma_0 \Gamma_{sd} \sigma_{si}^2} + \frac{1}{\gamma_i \Gamma_{id} \sigma_{id}^2} \right) \tag{13}$$

The function is logarithmically processed and the formula changes as follows.

$$\log P_{out} = -(n+1) \log \gamma_0 + \sum_{i=1}^{n} \log(\gamma_0 \Gamma_{sd} \sigma_{si}^2 + \beta_i \Gamma_{id} \sigma_{id}^2) - \sum_{i=1}^{n} [\log \gamma_i + 2 \log(\sigma_{si} \sigma_{di} \Gamma_{sd} \Gamma_{id})] + \log \left[C(n) \frac{1}{\Gamma_{sd} \sigma_{sd}^2} \cdot \frac{1}{(E_t)^{n+1}} \right] \tag{14}$$

The minimum disruption probability function based on energy constraints is established by the Lagrangian construction method.

$$I(i) = -(n+1) \log \gamma_0 + \sum_{i=1}^{n} \log(\gamma_0 \Gamma_{sd} \sigma_{si}^2 + \beta_i \Gamma_{id} \sigma_{id}^2) - \sum_{i=1}^{n} [\log \gamma_i + 2 \log(\sigma_{si} \sigma_{di} \Gamma_{sd} \Gamma_{id})] + \lambda \left[\sum_{i=0}^{n} \gamma_i - 1 \right] \tag{15}$$

$$L = \arg\max \sum\nolimits_{i=1}^{n} [L(i) + I(i)] \tag{16}$$

$$\text{St:} \sum_{i=1}^{n} \gamma_i = 1 \tag{17}$$

$$\alpha(i) + \beta(i) = 1 \tag{18}$$

The routing function is determined by calculating the comprehensive weight of the link's transmission capacity. The optimal solution of the function is defined as the numerical value of the optimal route in the cluster.

C. IMPROVED MOTH SEARCH ALGORITHM TO SOLVE THE OPTIMAL FUNCTION

Moth search algorithm is a novel swarm intelligence algorithm that studies the use of moths instead of drones. The optimal solution of the objective function is solved by updating the position of moths. The moth search algorithm is updated by adding residual energy constraints when the location is updated [27]. The improved algorithm has the advantages of simple computation and increased robustness.

The position of the moth population is determined by the population matrix, and the individual moth updates the global optimal solution of the solution function by optimizing the position of the space. Because cluster network adopts cluster communication, the global optimal computing complexity is reduced.

$$m = [m_1, m_2, \cdots, m_n]^T \tag{19}$$

$$M = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1p} \\ m_{21} & m_{22} & \cdots & m_{2p} \\ m_{31} & m_{32} & \cdots & m_{3p} \\ m_{n1} & m_{n2} & \cdots & m_{np} \end{bmatrix}^T \tag{20}$$

The n is the number of moth cluster individuals and p is the dimension of the solution problem and is the number of UAV links. Moth individual fitness is introduced for optimizing individual positions.

$$OM = [OM_1, OM_2, \cdots, OM_n]^T \tag{21}$$

The flame parameter was determined to represent the optimal solution of the function, where the flame is the best position of the current individual moth position, and the study updated the position matrix and the position and energy adaptation position.

$$D = [d_1, d_2, \cdots, d_n]^T \tag{22}$$

$$E = [e_1, e_2, \cdots, e_n]^T \tag{23}$$

$$OD = \begin{bmatrix} D_{11} & D_{21} & \cdots & D_{1p} \\ D_{21} & D_{22} & \cdots & D_{2p} \\ \cdots & \cdots & \cdots & \cdots \\ D_{n1} & D_{n2} & \cdots & D_{np} \end{bmatrix}^T \tag{24}$$

$$OE = \begin{bmatrix} E_{11} & E_{21} & \cdots & E_{1p} \\ E_{21} & E_{22} & \cdots & E_{2p} \\ \cdots & \cdots & \cdots & \cdots \\ E_{n1} & E_{n2} & \cdots & E_{np} \end{bmatrix}^T \tag{25}$$

Under the constraint of residual energy, the position of individual moths is continuously updated to be closer around the flame. After each iteration the individual continuously adjusts the update rate according to the individual position adaptation. Thus the solution of the function can be transformed into the following function.

$$L = S(OM, OD, OE) \tag{26}$$

TABLE 2. Algorithm establishment of UAV cluster network structure.

Algorithm: Improved Moth Search Routing Algorithm

Input: Location, residual energy, link connectivity matrix, etc.
Output: Best Routing Link
Begin:
  Step 1 The cluster head is determined
    for (i=1:n)
      Calculate the remaining energy of nodes
    end
  Step 2 Establishing communication links between nodes
    for (j=1:n)
      The remaining energy of the node is calculated
      The distance between nodes is calculated
    end
  Step 3 The optimal routing choice function is solved
    Establish a moth position matrix
    Establish a moth residual energy matrix
    for (k=1:p)
      Executing Moth Search Function Iteration
    end
  Solving the Optimal Solution of Moth Search Function
end

III. ALGORITHM DESIGN

A. ALGORITHM DESIGN

The improved moth search algorithm is designed to update by updating the position. Under the constraint of residual energy, the positions of individual moths are iterated, the residual energy of each iteration is calculated, and finally the optimal solution of the L-function is solved. The pseudo code of the algorithm design is shown in Table 2.

IV. SIMULATION VERIFICATION

A drone cluster experiment was organized to verify the advanced of the recalculation method. Some clusters were established by networking 50 UAVs. Parameters of UAV cluster communication were collected for simulation in MATLAB2020. Different algorithms were designed to establish the optimal routing [28], [29]. Two metrics, network coverage and residual energy, were calculated for comparing the utility of the algorithms.

A network of 50 Chinese DJI branded drones was created. In the space of 1000 cubic meters, the cluster mesh was designed by the following parameters. The coordinates of the source node UAVs are (50, 50), the coordinates of 50 UAVs are summarized in Table 3.

A. PARAMETER SETTINGS

The data from the UAV tests are fed into the simulation platform. Table 4 shows the specific values of the parameters. Simulation metrics were calculated containing network topology, node residual energy and communication time. Three mainstream algorithms were identified for comparing the performance of the designed algorithms. The experiments were executed according to the collaborative communication process and the experimental results are known to be repeatedly implemented [29], [30].

TABLE 3. About 50 UAVs in the low altitude 1000 m^3 space (/m).

NO'	horizontal coordinate	vertical coordinate	NO'	horizontal coordinate	vertical coordinate
1	81.47	90.58	26	35.00	19.66
2	91.34	63.24	27	61.60	47.33
3	27.85	54.69	28	83.08	58.53
4	96.49	15.76	29	91.72	28.58
5	95.72	48.54	30	75.37	38.04
6	14.19	42.18	31	7.59	5.40
7	79.22	95.95	32	77.92	93.40
8	3.57	84.91	33	56.88	46.94
9	67.87	75.77	34	33.71	16.22
10	39.22	65.55	35	31.12	52.85
11	70.60	3.18	36	60.20	26.30
12	4.62	9.71	37	68.92	74.82
13	69.48	31.71	38	8.38	22.90
14	3.44	43.87	39	15.24	82.58
15	76.55	79.52	40	99.61	7.82
16	48.98	44.56	41	10.67	96.19
17	70.94	75.47	42	77.49	81.73
18	67.97	65.51	43	8.44	39.98
19	11.90	49.84	44	80.01	43.14
20	34.04	58.53	45	18.18	26.38
21	75.13	25.51	46	13.61	86.93
22	69.91	89.09	47	54.99	14.50
23	54.72	13.86	48	62.21	35.10
24	25.75	84.07	49	40.18	7.60
25	81.43	24.35	50	12.33	18.39

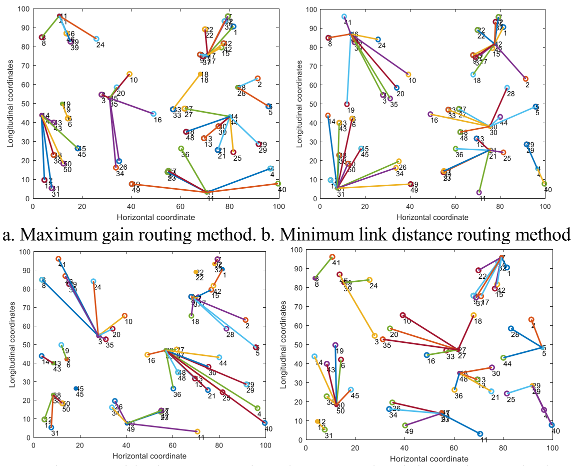
TABLE 4. Simulation parameter setting.

Parameter	Parameter Value
Number of UAVs	50
Network coverage area	1000m^3
Energy consumed for signal transmission	50J/ m^3
Energy amplification for signal amplification	10J /m^3
Maximum number of rounds	1000round
System Energy	10000J

B. COMPARISON OF DIFFERENT ALGORITHMIC NETWORK TOPOLOGIES

Fifty cluster network nodes are connected and the nodes send data to other nodes through neighboring nodes. The source and destination nodes are connected through different links, and the experiments evaluate the performance of different algorithms by simulating the residual energy, coverage and link SNR of different routing methods [16], [31], [32]. The comparison algorithms contain the optimal algorithms for (a) Maximum gain routing method, MAGA. (b) Minimum link distance routing method, MILD. (c) Maximum residual energy routing method, MAEN. (d) Integrated weight routing method, INWE. Figure 2 shows the network topology of different routing methods for two subcluster networks composed of 50 UAV clusters.

As can be seen from the four subplots in Figure 2, the clustered network is divided into several subclustered subnetworks. The coordinates of cluster heads are different in different selection algorithms, but the remaining energy of other nodes is the same. The coverage of the network is also different. Figure a shows the simulation results of the maximum channel gain screening cluster head (CH). In Fig. a, the cluster heads are widely distributed, which indicates that the network coverage is extended. Figure b shows the simulation results of filtering cluster heads (CH) based on the average distance. The node with the smallest combined distance of all links is identified as the cluster head, and the other nodes in the system are connected to the nearest cluster head



a. Maximum gain routing method. b. Minimum link distance routing method

c. Maximum residual energy routing. d. Integrated weight routing method.

FIGURE 2. **Simulation of network structure topology for different algorithms.**

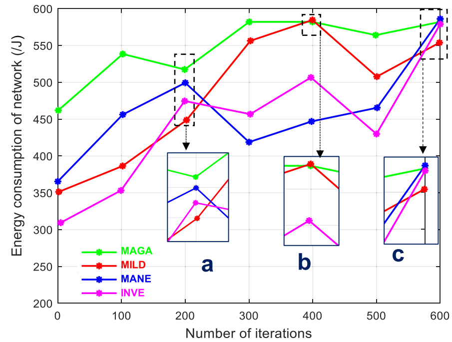


FIGURE 3. **Simulation of Comparison of energy consumption of network nodes. (a) Comparison of energy residuals for 200 iterations. (b) Comparison of energy residuals for 200 iterations. (c) Comparison of energy residuals for 200 iterations. MAGA is maximum gain routing method, MILD is minimum link distance routing method, MANE is maximum residual energy routing method, INVE is integrated weight routing method.**

to form the sub-cluster communication structure. Figure c shows the simulation results of the maximum residual energy cluster head selection. Nodes with larger residual energy in the link are filtered out, and other nodes do not participate in communication outside the subcluster. Figure d shows the simulation results of cluster head selection based on the combined distance and energy weight constraints. The node with the larger combined weight of distance and energy in the link is identified as the cluster head, and the other nodes are connected to the cluster head. The comparison of the four simulation plots shows that the channel gain and combined weight based algorithm has a large distribution space and the network is partitioned to communicate through different subclusters. The distance based and energy based cluster head screening methods have the disadvantages of single structure and restricted distribution, but the link robustness of both methods is good.

C. COMPARISON OF ENERGY CONSUMPTION OF NETWORK NODES

Cluster heads are determined by filtering with different algorithms. Signals are broadcast from the source node to the cluster head node. Inside the clustered network, signals are sent to all nodes connected through the link. The energy of the cluster head is consumed due to receiving or sending signals, and the energy of the normal nodes is consumed by collecting information and receiving signals. Different network distributions and routing consume different amounts of energy, so a study on the node survival time of the network under different routing methods was conducted [33], [15], [8]. The average node survival period of the system was compared for four different algorithms. After 600 iterations, the average energy consumed by the system was regionally consistent. The detailed comparison process is shown in Figure 3.

Figure 3 shows the comparison results of the simulation of energy consumption of the cluster network with different routing methods. From the figure, it can be seen that the energy consumption of the system fluctuates up and down with the increase in the number of iterations. This indicates that the energy consumption in UAV cluster communication keeps changing with the replacement of routing links. The energy consumption of algorithm MAGE is the largest, but the fluctuation of energy is the smallest. This is because the energy consumed for communication is increased to ensure that the system has good channel gain. The network nodes of algorithm MILD consume consistent energy with little fluctuation, which is because the network energy consumption is related to the link distance. Long distance links consume more energy and short distance links consume less energy. Algorithm MANE shows that the consumption of energy under the energy constraint varies widely, and the energy consumption is small at the early stage when the constraint is large, and the frequent switching of links consumes a large number of nodes at the later stage because the remaining energy of nodes is not very different, and when the number of iterations exceeds 400, the energy of remaining nodes tends to be consistent and the value of consumed energy starts to decrease. The energy consumed by the network nodes of algorithm INVE is constrained by two control factors. Under the distance constraint, the energy consumption of the system gradually increases, when the energy consumption is constrained, the energy of the system starts to gradually decrease again. After 600 iterations of the four algorithms, the remaining energy of the nodes of the system is approximately the same and the energy consumed by the system is similar. There is a comparison in the figure shows that the system consumes less energy, and the curves with small fluctuations in the system energy consumption curve are algorithm MILD and algorithm INVE Therefore, the energy consumption of UAV communication is significantly affected by the length of the link.

D. BER OF UAV SWARM NETWORK SYSTEMS

BER is an important metric for evaluating the quality of service of a channel [34], [35]. The parameters of the four

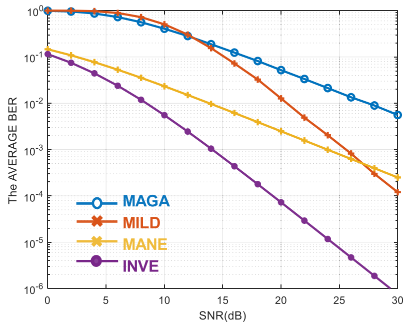


FIGURE 4. Simulation comparison of the system average BER of the 4 algorithms.

routing methods have a large relationship with BER, so BER is identified as an evaluation metric. A BER experiment on the four routing algorithms was organized and the system average BER was calculated and the simulation structure is shown in Figure 4.

Figure 4 shows that the BER of the UAV cluster communication keeps decreasing as the signal-to-noise ratio keeps increasing. This indicates that the network topologies designed by the four algorithms can provide quality communication services. The channel gain of Algorithm MAGE has a significant function with BER and other parameters, so the BER variation of Algorithm MAGE is not linear as the signal-to-noise ratio increases. The distance of Algorithm MILD is non-linearly related to the BER, which is due to the exponentially decreasing effect of the change in distance on the BER. And the variation of Algorithm MANE shows that the relationship between the residual energy and the effect of BER of the signal is not significant. This is because the energy consumed to send the correct byte or to send the wrong byte is the same. The curve trend of Algorithm INVE shows that the BER of the system is not linearly related to the signal-to-noise ratio under the constraints of distance and energy, but the BER decreases at the fastest rate. This indicates that the system can provide better network service quality.

E. DISCUSSION OF THE RESULTS

The results of three experiments on network routing, network residual energy, and network BER are compared. The results show that in the network topology and routing experiments, the best data results are obtained for 4 Algorithms, and the network structure meets the application needs. In the study of network residual energy, Algorithm MILD and Algorithm INVE have the best results for residual energy values, where Algorithm INVE has the least variation in residual energy. In the experiments of network BER, the best results are obtained for Algorithm MANE and Algorithm INVE, which indicates that the algorithms can provide quality communication service quality. In summary, although the topology of Algorithm INVE is not as good as Algorithm MAGE, Algorithm INVE is the best algorithm for routing in the UAV cluster network in terms of the average value of the three metrics.

V. CONCLUSION

To solve the problem of excessive energy consumption in the routing of large-scale UAV cluster networks, a routing method based on distance and energy constraints is proposed. The UAV cluster network is divided into multiple cluster communities. Cluster heads are determined by comparison of the remaining energy of nodes. Within the cluster groups links are constructed by comparison of two weights such as residual energy of nodes and length of links. By comparing the simulation results sent by different routing algorithms, the improved algorithm can meet the requirements of practical applications in terms of network topology, residual energy and BER metrics.

The routing method based on the integrated weight of distance and residual energy has the advantages of simple calculation and high residual energy of the network. The network coverage of the UAV cluster network is extended and the energy of the nodes in the network system is saved by the changing link selection. After 600 iterations of communication nodes, the residual energy of the cluster network starts to equalize, the network structure is not changing, and the quality of communication service is improved.

Due to the experimental conditions, communication between UAVs and unmanned vehicles has not been verified. In the near future, experiments on communication between UAV clusters and ground base stations will be organized. The interference between UAV communication signals gets attention due to the increase in the number of network nodes. From the current research results, it can be seen that the routing method based on the combined weight of distance and vocal energy can be a selection method with low energy consumption and wide coverage. The proposed improved method has good practicality and generality in UAV cluster networking.

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