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RESEARCH ARTICLE

Multi-UAV Relay Connectivity Optimization for Heterogeneous Users Based on Load Balancing and Throughput Maximization

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ABSTRACT By relaying messages between users, unmanned aerial vehicles (UAVs), which are frequently utilized in the communication industry, can be used as airborne communication relays to resolve connectivity problems. In order to effectively connect a large number of heterogeneous users dispersed on the ground, we deploy a large number of UAVs for reliable relay coverage and message transmission between users. We initially put forth a relay coverage algorithm that continuously optimizes the position of UAVs and the cell division of ground users in order to provide users with full coverage. Second, we study several relay message forwarding methods between UAVs while taking into account the features of heterogeneous users. A relay selection method, which takes the relay link throughput as the optimization goal, is proposed to ensure full connectivity between UAVs. Finally, we contrast and analyze how various relay forwarding methods affect the effectiveness of the relay network. The experimental results demonstrate that the proposed relay coverage algorithm can balance the UAV relay load better and reduce transmission delay, while the suggested relay selection strategy can minimize the number of isolated UAVs and maximize the throughput of UAV relay links.

INDEX TERMS UAV, relay connectivity, heterogeneous users, relay message forwarding, load balancing, throughput.

I. INTRODUCTION

Due to their low cost and flexible deployment, UAVs [1], [2] have found extensive usage in the military, civil, and commercial fields for operations like swarm operation [3], emergency rescue [4], and security [5]. For instance, when the ground-based communication infrastructure is destroyed by the natural disaster, UAVs can be used to establish temporary communication links to support rescue operations.

It can be seen that connectivity issue is a major concern for ensuring that users have reliable communication links. Users that are unable to contact directly can still establish connections by forwarding messages owing to the communication relay [6], [7], [8], [9]. Direct communication is actually prevented by a wide range of barriers, including over-the-horizon communication that occurs outside the connection range, link interruption due to interference in complex situations, incompatible communication systems that prevent direct communication between heterogeneous users, and so on. The communication relay technology [10], [11], [12] can offer effective answers to these problems. From the perspective of the causes behind the requirement for relaying, it can be said that communication relay technology addresses two main connectivity issues: the first is the connectivity issue of over-the-horizon communication, and the second is the connectivity issue of incompatible communication systems.

Owing to the unique advantages, UAVs are frequently utilized as airborne base stations and aerial relays in the communication field to establish wide-area coverage connection, giving users access to reliable, timely, and on-demand communication services [13], [14], [15], [16], [17]. The connectivity of heterogeneous users faces significant

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difficulties because of their incompatible communication systems. To solve this problem, UAV can be utilized as a relay to offer reliable communication links for heterogeneous users. There are two ways to utilize UAV as relay to address the issue of user connectivity: single UAV relay and multi-UAV relay [18], [19], [20], [21], [22]. The primary purpose of the single UAV relay mode, which has a straightforward research model, is to address the communication connection of small-scale users. Multi-UAV relay mode, which addresses the connectivity issue faced with large-scale users, has gained prominence and created extra challenges.

As we know, large-scale operations have emerged as a crucial feature of warfare due to the overall trend of space-air-ground integration. The number of platforms and operational range increase significantly in the context of large-scale operation. Multiple UAVs can be employed to offer relay links between platforms, which can greatly enhance connectivity and meet the aforementioned requirements. In the research of multi-UAV relay, to assure connectivity—which includes both connectivity between users who need to be relayed and connectivity between various UAVs—is the key to solving the challenge of multi-UAV relay model. Researchers frequently convert the problem of the connection of users into the coverage problem of users by deploying a specific number of UAVs to cover the users. And there are some research findings on using UAVs to provide coverage services to users on the ground.

Lin et al. [23] suggested an adaptive deployment method to identify optimal UAV places to enhance user coverage probability and lower UAV communication energy consumption. In their study of a UAV-assisted self-organized device-to-device network, Zhong et al. [24] suggested an alternating optimization method to jointly optimize relay deployment, channel allocation, and relay allocation to maximize the capacity of the relay network. The top and lower bounds of the coverage probability for hovering and mobile UAVs were each independently assessed in [25]. In order to reduce the maximum energy consumption of UAVs and provide coverage for ground users, Lu et al. [26] presented a hybrid genetic algorithm. In addition, Chen et al. [27] separated the horizontal and vertical aspects of the UAV deployment problem and suggested a multi-population genetic algorithm to address the issue. The results showed that the proposed algorithm performs better than a standard genetic algorithm. Zhong et al. [28] suggested a novel genetic algorithm based on the 2-D placement approach to attain the maximum coverage probability of users, which is similar to the decoupling concept in [27]. The afore-mentioned studies provide different coverage service schemes for ground users from various perspectives, and all of them are capable of meeting the target optimization requirements.

However, as can be seen from the above literatures, UAVs are deployed to cover ground users and relay information, but the connectivity of inter-UAVs is not considered. Using D2D communication technology [29], [30], the connectivity issue between relay UAVs can be resolved partly. UAVs within the mutual communication radius can communicate directly, and for UAV connections beyond the communication radius, a suitable UAV must be added to or chosen for relaying in the UAV relay network. Different relay selection methods have been developed by researchers for various communication system optimization metrics [31], [32], [33], [34], [35]. A relay selection method based on the best harmonic mean determined by the signal-to-noise ratio was suggested in [31]. In wireless cooperative communication systems, Yuan et al. [32] rank backup UAVs based on outage probability, and propose a relay selection algorithm based on unscented Kalman filtering and greedy to select the UAV with the lowest outage probability as the next relay node. However, the scenario for this study is to select a relay UAV for both source and destination UAVs in the air.

In the aforementioned literature, studies on multi-UAV relay services primarily concentrate on relay coverage for homogeneous users who share the same types of function and effect, while there is a lack of research on the relay connectivity of heterogeneous users who have incompatible communication systems. The problem of connectivity among a huge number of large-scale heterogeneous users is becoming more difficult as a result of the development of data link types and simultaneous access to many types of networks.

In this paper, we employ a number of UAVs to relay information in order to address the connectivity challenge of communication for a large number of heterogeneous users. Each UAV is equipped with multiple different information processing modules that may relay user data within the covered area and process it. The concept of Voronoi diagram division is used to divide the coverage area into several small areas in accordance with each UAV's capacity and communication range. The small areas are covered by the UAVs for relay coverage. In this process, this paper develops a relay coverage algorithm to identify the proper number and placement of UAVs. Each UAVs processes the transmitted messages of users who are inside their own coverage area. This paper suggests a relay selection strategy to selects the most appropriate UAV to establish a communication link between UAVs that are outside the communication range of each other. Also, this paper provides various distinct relay information forwarding methods, compares them, and analyzes them in the context of information forwarding with UAVs. The established connection link's throughput can be increased by using the relay selection strategy.

To recap, the main contributions of this paper are summarized as follows:

1) Separating the multi-UAV relay connectivity problem into two sub-problems, relay coverage and relay selection, to offer coverage connection to ground separated heterogeneous users.

2) When implementing reliable relay coverage, the coverage area is divided by using the proposed relay coverage algorithm to determine the best placement for relay. This

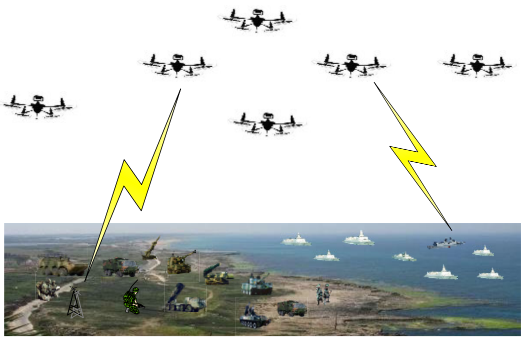


FIGURE 1. Relay coverage scene.

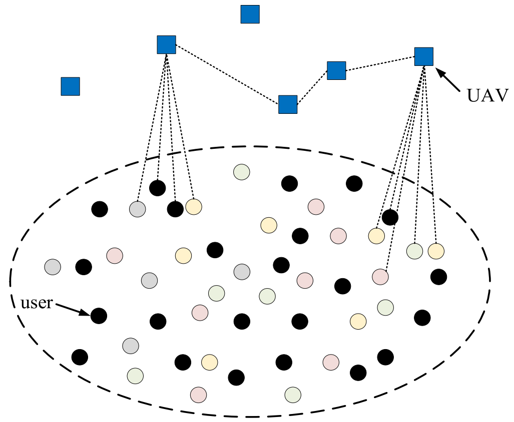


FIGURE 2. Model description diagram.

algorithm can optimize the load balance rate and transmission delay performance index of relay network.

3) To ensure that there are no isolated UAVs, different relay information forwarding methods are taken into consideration when establishing connectivity between relay UAVs. The relay selection strategy is created to maximize the throughput of the relay link while the throughput of the relay link is taken as the optimization objective. The metrics of relay network processing delay and relay link Signal to Interference plus Noise Ratio (*SINR*) under various relay information forwarding methods are also taken into consideration.

This paper is structured as follows. The system model and pertinent model representations are presented in Section II. The proposed relay coverage algorithm and relay selection strategy will be discussed in Section III to provide a solution. The simulation results and comparison analysis will be presented in Section IV. The conclusion and the prospects of future work will be provided in Section V.

II. SYSTEM MODEL

This section will describe the relay coverage scene with UAVs and model it. The corresponding representations and calculations will then be displayed.

A. PROBLEM DESCRIPTION

Fig. 1 depicts the scenario that was the subject of this paper. A huge number of combat units are dispersed across land and water in the trend of joint warfare, and each combat unit carries out its own task while working cooperatively with the others to carry out joint warfare operations. We contemplate deploying a specific number of UAVs to relay the communication information since each combat unit cannot directly communicate with one another owing to distance or incompatible communication systems. The UAVs use the decoding and forwarding relaying method in the relaying process because they need to process information from different communication systems.

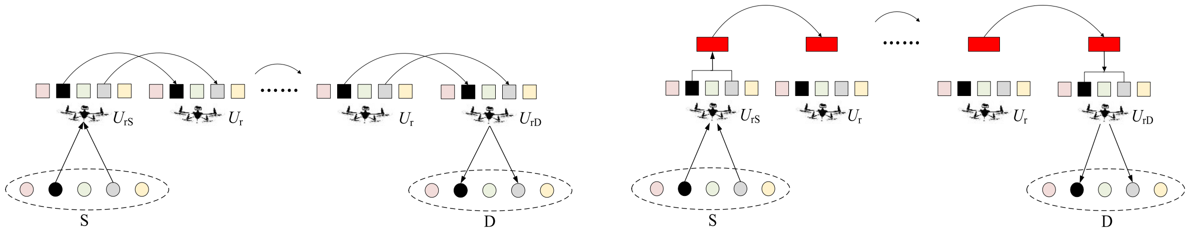
In order to more effectively address the problem, the scenario is described mathematically as a model of multiple UAV nodes relaying to cover ground user nodes. Numerous heterogeneous user nodes dispersed over an area are reliably covered by multiple UAV nodes. User nodes achieve intercommunication through one or more UAV nodes to provide a connectivity link, which is showed as Fig. 2. The area that each UAV covers may have a variety of users due to the various communication systems used by ground users. When transmitting different types of information, UAVs may use various information forwarding methods.

Fig. 3 presents two fundamental relay information forwarding methods. The non-associative forwarding (NAF) method is illustrated in Fig. 3(a), where the user node in the source area S transmits relay information to its corresponding UAV node U_{rS}, who decodes and processes the relay information. Additionally, the U_{rS} sends the relay information independently to the UAV node U_{rD} corresponding to the destination area D with the loaded signal processing modules. After that, the U_{rD} distributes the relay information independently to each target user node. The associated forwarding (AF) method is depicted in Fig. 3(b), in which the UAV node U_{rS} merges and pack-ages the relay information for transmission to U_{rD}, who decomposes and forwards it to the target user node. The three actual forwarding methods—NAF, AF, and hybrid for-warding (HF)—are represented in Fig. 4.

B. MODEL BUILDING

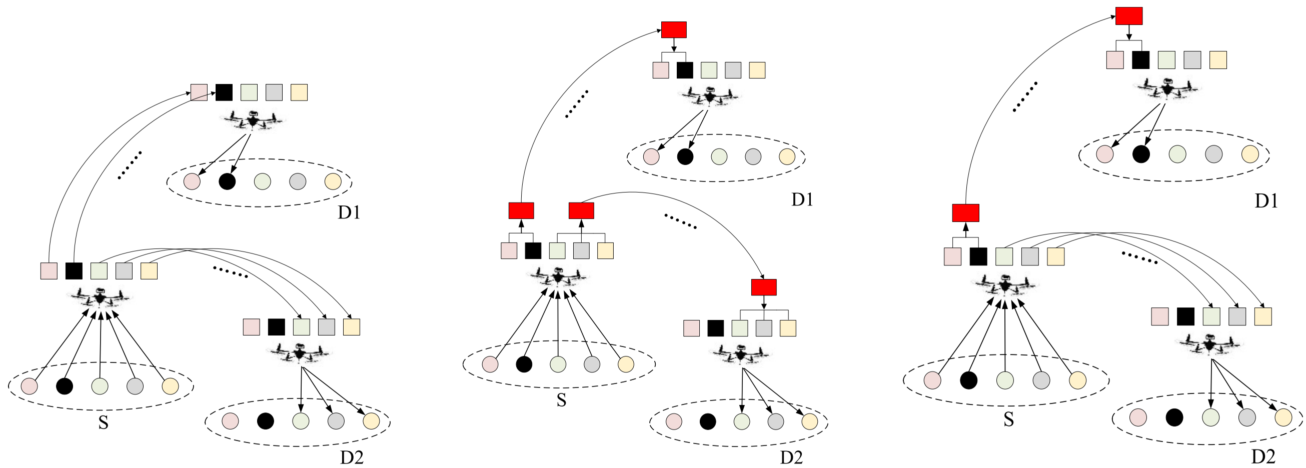
In the aforementioned model, we assume that there are N UAVs and P ground users. They are denoted by the symbols $\{U_1, U_2, \cdots U_N\}$ and $\{G_1, G_2, \cdots G_P\}$, respectively. The UAV's flight altitude is H. The UAV's Cartesian coordinate is given as $\left(U_{ix}, U_{iy}, H\right)$, while the ground users' coordinate is expressed as $\left(G_{jx}, G_{jy}\right)$. Defining that $x_{i,j}$ indicates the coverage connection relationship between UAV node U_i and ground user node G_j. When G_j is connecting with $U_i, x_{i,j} = 1$; Otherwise, $x_{i,j} = 0$. Assuming that r_c is the UAV node's coverage radius, then $r_t = \sqrt{{r_c}^2 + H^2}$ is its communication radius.

The communication link's throughput is denoted by $R = B\log_2(1 + SINR)$ in accordance with Shannon's formula, where B stands for the channel bandwidth. We create the following definition in order to make the method more understandable. Assuming that the number of UAVs inside



(a) Non-associative forwarding. (b)Associative forwarding.

FIGURE 3. Two basic relay information forwarding methods.



(a) Non-associative forwarding illustration. (b) Associative forwarding illustration. (c) Hybrid forwarding illustration.

FIGURE 4. Three actual forwarding method examples.

the communication range of UAV U_j is F_j, define ε_{kj} to indicate whether U_k, where U_k is the UAV in F_j, interferes with U_j. When U_j is receiving signals and U_k is broadcasting signals, it is determined that U_k interferes with U_j, and ε_{kj} is set to 1; otherwise, it is determined that U_k does not interfere with U_j, and ε_{kj} is set to 0.

$$\varepsilon_{kj} = \begin{cases} 1 & interference \\ 0 & non-interference \end{cases} \tag{1}$$

The *SINR* γ_{ij} of the communication link between the UAV U_i and U_j is defined as the following expression.

$$\gamma_{ij} = \frac{P_i^{(\mathrm{T})}\tau \left|h_{ij}\right|^2}{\sum\limits_{k=1,k\neq i}^{F_j} \varepsilon_{kj} P_k^{(\mathrm{T})}\tau \left|h_{kj}\right|^2 + N_0} \tag{2}$$

where $P^{(\mathrm{T})}$ stands for the UAV transmit power. $P_k^{(\mathrm{T})}$ denotes the transmitting power of the $k-$th UAV node within the communication radius of the UAV node U_j, and $\sum\limits_{k=1,k\neq i}^{F_j} \varepsilon_{kj} P_k^{(\mathrm{T})}\tau \left|h_{kj}\right|^2$ denotes the total amount of the interference caused by other UAV nodes to the destination node during each relay message transmission. τ denotes the path loss constant. h denotes the channel gain. N_0 denotes the power of noise.

Under different forwarding modes, UAVs independently transmit different numbers and types of relay information. Therefore, the number of relay information λ_k transferred in the link has an impact on the *SINR* for the three types of the relay information forwarding method. Given that there will be relay messages λ_k sent through the U_k, the *SINR* is written as:

$$\gamma_{ij} = \frac{P_i^{(\mathrm{T})}\tau \left|h_{ij}\right|^2}{\sum\limits_{k=1,k\neq i}^{F_i} \varepsilon_{kj} \lambda_k P_k^{(\mathrm{T})}\tau \left|h_{kj}\right|^2 + N_0} \tag{3}$$

It is clear that the number of relay information λ_k between the three methods varies. The size of λ_k in NAF is determined by the quantity of source user nodes that need to be relayed. The amount of λ_k in AF and HF is dependent on the quantity of relay messages that have to be merged and packaged, which is less than the quantity of source user nodes that need to be relayed. Consequently, the communication throughput between UAV node U_i and node U_j is defined as:

$$\begin{aligned} R_{ij} &= B\log_2\left(1+\gamma_{ij}\right) \\ &= B\log_2\left(1+\frac{P_i^{(\mathrm{T})}\tau \left|h_{ij}\right|^2}{\sum\limits_{k=1,k\neq i}^{F_j} \varepsilon_{kj} \lambda_k P_k^{(\mathrm{T})}\tau \left|h_{kj}\right|^2 + N_0}\right) \end{aligned} \tag{4}$$

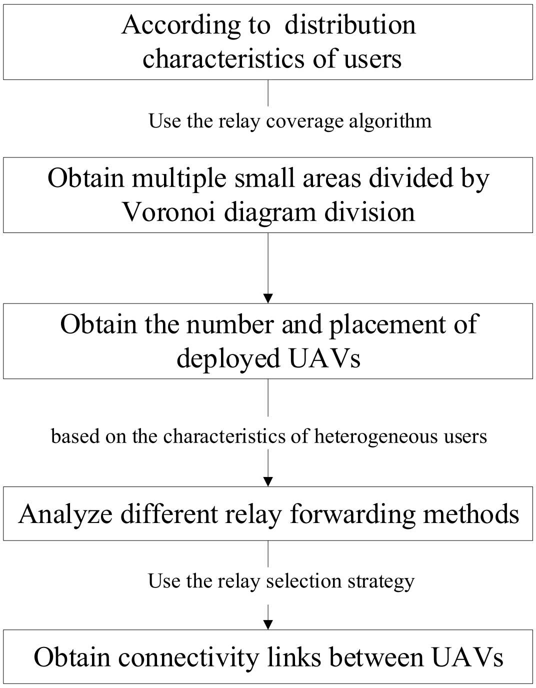


FIGURE 5. The connectivity optimization method flow diagram.

There are two stages to the communication process when UAV U_r serves as a relay between U_i and U_j. The throughput can be defined as the following expression.

$$\begin{cases} R_{ir} = B\log_2\left(1+\gamma_{ir}\right) \\ R_{rj} = B\log_2\left(1+\gamma_{rj}\right) \end{cases} \tag{5}$$

III. CONNECTIVITY OPTIMIZATION METHOD DESIGN

The UAVs not only need to cover the ground users in order to achieve connectivity between any two users, but also need have a reachable connectivity link between the UAVs. As a result, we transform this problem into two subproblems to solve: relay coverage and relay selection. Relay coverage aims to address the issue of connectivity between users and relay UAVs, while relay selection aims to address the issue of connectivity among UAVs. In order to better illustrate the connectivity optimization method proposed in this paper, a method flow diagram is shown in Fig.5.

The relay coverage algorithm is designed for an iterative solution to determine the number and placement of relay UAVs. The coverage area is initially divided into multiple small regular areas based on the coverage radius of the UAVs. UAVs within the communication range employ D2D communication technology to directly convey relay information during the relay. The appropriate UAV is chosen for relaying the UAVs beyond the communication radius or with limited communication conditions by designing a relay selection strategy. Different relay information forwarding methods between UAVs are taken into consideration throughout the selection process in order to build a reliable connectivity link with the relay link's throughput as the optimization objective. Additionally, the performance of various relay information forwarding methods is evaluated and contrasted in terms of the relay network's processing delay and the relay link's *SINR*.

In order to assess the design efficacy of the algorithms and strategies, three performance evaluation metrics are defined as follows.

A. PERFORMANCE EVALUATION METRICS

1) LOAD BALANCING

Each user has different messages that need to be transmitted as a result of the differences across heterogeneous users. When calculating the load of the UAV, we mainly consider the number of users connected to the UAV (Q) and the average "packet in" message arrival rate of these users (C) to the connected UAV. Since the order of magnitude of Q and C is inconsistent, after normalization, the load M_i of UAV node U_i is defined as

$$M_i = aQ_i + bC_i \tag{6}$$

where $a+b=1$ and $Q_i = \sum_{j=1}^{P} x_{i,j}$. To simplify the study, in this paper, we assume that a=b=0.5. And they can be adjusted according to the practical scenario requirements.

According to the load of each UAV, we use variance to represent the load balance rate (V) of the relay network, which is expressed as

$$\begin{cases} \overline{M} = \frac{1}{N}\sum_{i=1}^{N} M_i \\ V = \frac{\sum_{i=1}^{N}\left(M_i-\overline{M}\right)^2}{N} \end{cases} \tag{7}$$

where $\overline{M}$ denotes the average value of the UAV load. The smaller the value of V is, the more balanced the relay load of each UAV.

2) TRANSMISSION DELAY

The UAV is deployed at an appropriate location to provide relay services for users. The quality of the location can be reflected in the light of the time consumed by transmitting information between UAV nodes and user nodes. Since the transmission delay between links is mainly affected by the distance of nodes, we utilize the distance of nodes to represent the transmission delay index. The link transmission delay between UAV U_i and its connected user G_j is defined as

$$T_{U_i} = \sum_{j=1}^{P} d\left(U_i, G_j\right) \bullet x_{i,j} \tag{8}$$

Therefore, the average transmission delay of the whole relay network is expressed as

$$T_t = \frac{1}{N}\sum_{i=1}^{N} T_{U_i} \tag{9}$$

3) THROUGHPUT

The relay network's overall performance and transmission rate are significantly impacted by the relay selection result. In order to choose an appropriate relay UAV node, the proposed relay selection strategy tries to maximize the relay link throughput. Equation (5) states that when a relay link $U_i \rightarrow U_r \rightarrow U_j$ is constructed, its throughput is stated as [36]:

$$\begin{aligned} R_r &= \frac{1}{2}\min\left(R_{ir}, R_{rj}\right) \\ &\times \frac{B}{2}\min\left\{\log_2\left(1+\frac{P_i^{(\mathrm{T})}\tau|h_{ir}|^2}{\sum_{k=1,k\neq i}^{F_r}\varepsilon_{kr}\lambda_k P_k^{(\mathrm{T})}\tau|h_{kr}|^2+N_0}\right),\right. \\ &\left.\log_2\left(1+\frac{P_r^{(\mathrm{T})}\tau\left|h_{rj}\right|^2}{\sum_{k=1,k\neq r}^{F_j}\varepsilon_{kj}\lambda_k P_k^{(\mathrm{T})}\tau\left|h_{kj}\right|^2+N_0}\right)\right\} \end{aligned} \tag{10}$$

B. ALGORITHM AND STRATEGY DESIGN

1) RELAY COVERAGE ALGORITHM DESIGN

When solving the relay coverage problem, to optimize the load balance and transmission delay indexes of the relay network, the concept of area division is adopted in order to iteratively reach at the best cell division. After normalizing the load balance rate and transmission delay, the optimization objective of the algorithm can be expressed as

$$\min \quad \psi = V \bullet T_t \tag{11}$$

$$\text{s.t} \quad \sum_{i=1}^{N} x_{i,j} = 1, \forall j \tag{12}$$

$$x_{i,j} \in \{0, 1\}; \forall i, j \tag{13}$$

(11), the optimization objective of proposed algorithm, weights the load balance rate and the transmission delay performance indexes. (12) indicates that each user node is only connected with one UAV node. (13) constrains the connection relationship, and there are only two connection relationships between the user node and the UAV node.

To make the analysis easier, we assume that the coverage area is a regular area that is divided into multiple smaller and regular areas based on the UAV's coverage radius. The point with the shortest distance to other users is found in the small area according to the users dispersed in the area. The first center point in each small area is then used to define the point. According to all users in each small area, the UAV relay load in each area is calculated, and the load balance rate V and transmission delay T_t of the relay network are calculated. The first Voronoi diagram and the new divided area are derived from the first center point.

Algorithm 1 Relay Coverage Algorithm

Input: Randomly distributed users, the coverage area, the coverage radius of UAV

Output: The locations of center points, V, T_t

1. Divide the coverage area into several regular small areas;
2. Find the point with the shortest distance between the users in the small area, and define it as the first center point;
3. Calculate V, T_t, ψ;
4. According to the first center point, obtain the first Voronoi diagram and the newly divided area;
5. **if** $V_{n-1} - V_n \leqslant V_{th}$ $n \geqslant 2$
6. Iteration terminates;
7. **else** Find the next center point in the new area and return to 2;
8. **end if**
9. Get the$n$-th center point position,V,T_t

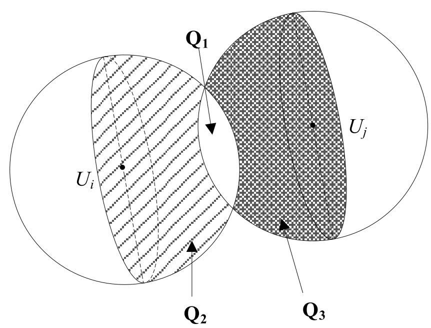


FIGURE 6. Define the area of Q_1, Q_2, Q_3.

As for the Voronoi diagram, the points in the small area of the Voronoi diagram are closest to the center point in the area where they are located and distant than the center points from all other areas. The second center point is determined in accordance with the result of the first Voronoi diagram. When the difference between V_{n-1} and V_n is smaller than the threshold value V_{th}, the aforementioned process is complete. The $n-$th center points, which are also the relay UAVs' projection locations, are derived. And the UAVs' coverage area is represented by the little areas of the $(n-1)-$th Voronoi diagram. The algorithm is set up as shown below.

Algorithm complexity analysis: Lines1-3 calculate load balance rate V and the transmission delay T_t, whose complexity is $O(2NP)$. And the lines 4-9 yield the $n-$th center point and the $(n-1)-$th Voronoi diagram, whose complexity is $O(nN^2P)$. Therefore, the overall time complexity of the algorithm is $O(nN^2P)$.

2) RELAY SELECTION STRATEGY DESIGN

In order to solve the relay selection problem, the D2D communication technology is used to build the communication

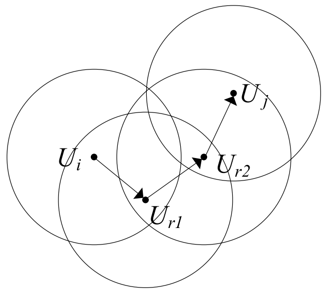


FIGURE 7. Schematic diagram of relay selection for multiple relay UAVs.

link between UAVs based on the relay coverage algorithm's derivation of the UAV position distribution. The UAVs that are within the communication range can establish a direct connection link. The appropriate UAVs are chosen to relay messages for the UAVs that are outside the communication range. In order to have reachable communication links between UAVs, the relay UAVs are chosen with the throughput of the relay link as the optimization objective.

Supposing that the UAV U_i and U_j who are out of the communication radius of each other need to transmit information. We assume that U_i serves as the source node, U_j serves as the destination node, and U_r serves as a relay node connecting U_i and U_j. We define the areas Q_1, Q_2, and Q_3 for the two UAVs that need relay. And then we draw the spherical coverage area with the coverage radius. It is depicted in Fig. 6.

The relay selection strategy is designed as follows.

1. If there is only a single UAV in Q_1, select the UAV as the relay node and execute step 8;
2. If there are multiple UAVs in Q_1, execute step 7;
3. If there is no UAV in Q_1, determine whether there is a UAV node in Q_2;
4. If there is no UAV node in Q_2, a new UAV node is placed in Q_1 at the location that maximizes the throughput of the link. Otherwise, all the UAVs in Q_2 are recorded as the set Θ. For the UAVs in Θ, draw the spherical coverage area with the communication radius and obtain the new $Q_1^{(1)}$, $Q_2^{(1)}$, $Q_3^{(1)}$;
5. In the Θ, find the elements that correspond to the area $Q_1^{(1)}$ which contains the UAVs. The elements are recorded as Θ_1. Given the number of elements in the set Θ_1, execute the steps 1 and 2. Then, the obtained relay node is recorded as U_{r1}
6. Given the number of UAVs in the $Q_1^{(1)}$, execute the steps 1 and 2. Then, the obtained relay node is recorded as U_{r2};
7. Calculate the throughput R between the candidate node and the source node and rank them. The node with the largest R is selected as the relay node;
8. For the obtained relay nodes, the connection link $U_i \rightarrow U_{r1} \rightarrow \bullet \bullet \bullet \rightarrow U_{rr} \rightarrow U_j$ with U_i and U_j is obtained. Finishing the selection.

Fig. 7 displays the pertinent descriptions for finding multiple relay UAVs in the relay selection process.

TABLE 1. Simulation parameters.

Parameter	Description
Coverage area	$20km \times 20km$
Number of ground users	200
Flight altitude of UAV	$1.8km$
Coverage radius of UAV	$5km$
Channel bandwidth	$180kHz$
Maximum transmitting power	$23dBm$
Interference noise	-120 dBm/Hz
Average information requests	[0, 2], random distributed

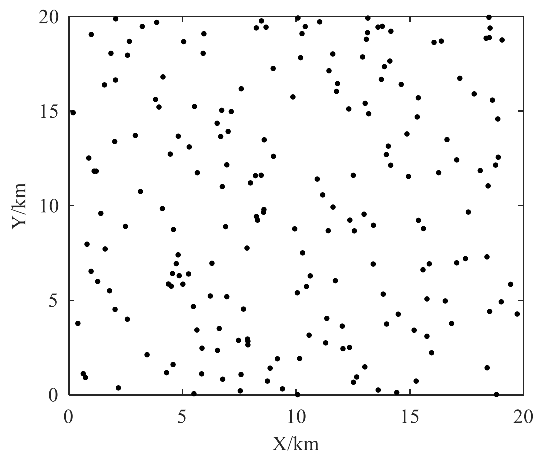


FIGURE 8. Randomly distributed ground users.

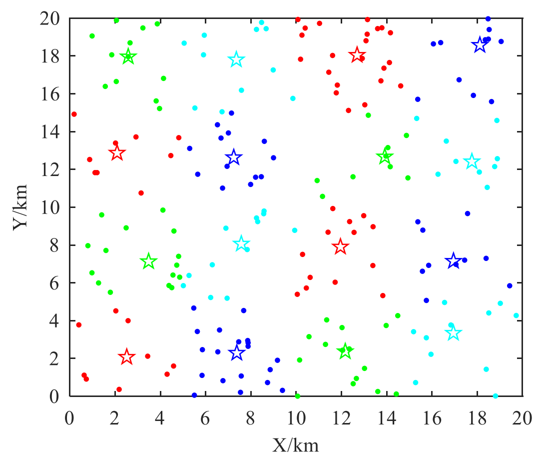
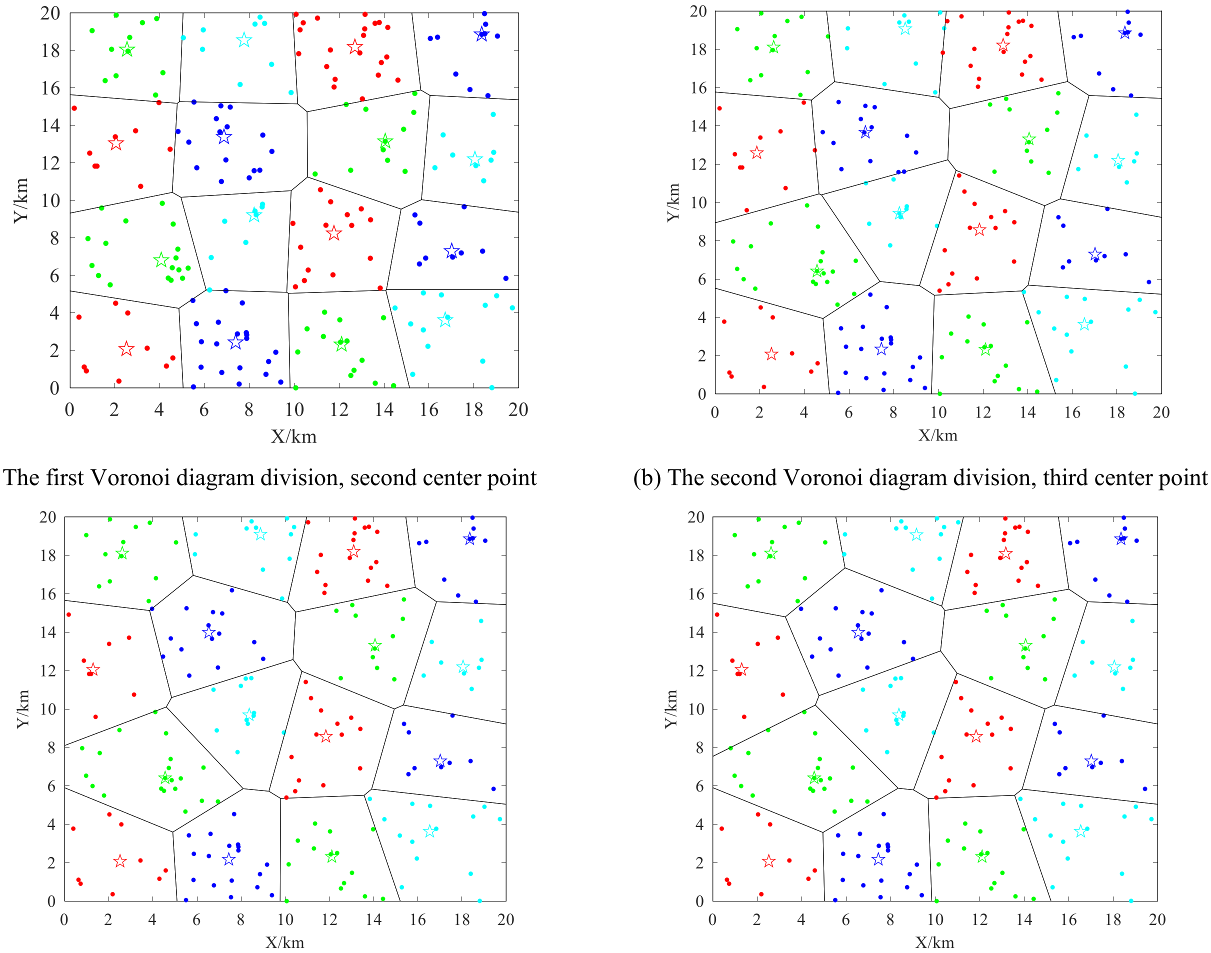


FIGURE 9. The location of the first center point.

IV. SIMULATION RESULTS AND ANALYSIS

A. SIMULATION PARAMETER SETTING

Based on MATLAB simulation platform, this section examines the effectiveness of the proposed method through comparison with other methods and numerical simulation. The experimental environment is configured as follows. (1) Software environment: Windows 10 Ultimate and Software MATLAB2016b. (2) Hardware environment:



(a) The first Voronoi diagram division, second center point

(b) The second Voronoi diagram division, third center point

(c) The third Voronoi diagram division, fourth center point

(d) The fourth Voronoi diagram division, fifth center point

FIGURE 10. **The Voronoi diagram division and the distribution of the center point.**

Processor: Intel (R) Core (TM) i5-6300HQ CPU @ 2.30GHz 2.30GHz; Memory: 8.00GB; System type: 64 bit Operating System.

To compare the relay load balancing rate and the transmission delay, the proposed relay coverage algorithm is compared with the Circle Fill Covering (CFC) algorithm and the k-means-based partitioning method. To evaluate and compare the throughput of the relay link, the proposed relay selection strategy is contrasted with distance-based strategy and Signal Noise Ratio strategy (SNR-based). Finally, the qualitative analysis and comparison of three relay forwarding modes are made. To verify the effectiveness of the proposed method, we set the number of the ground users as 200. The flight altitude of UAV is 1.8km. The coverage radius of UAV is set as 5km. The channel bandwidth is set as 180kHz. The maximum transmitting power is set as 23dBm. The path loss factor is set as 2. The averageinformation requests are chosen at random from a range of 0-2 packets/ms. It is worth noting that these parameters are set to better verify the effectiveness of the proposed method. In practical application, they can be changed as needed. For ease of tracking, we list the simulation parameters in Table 1.

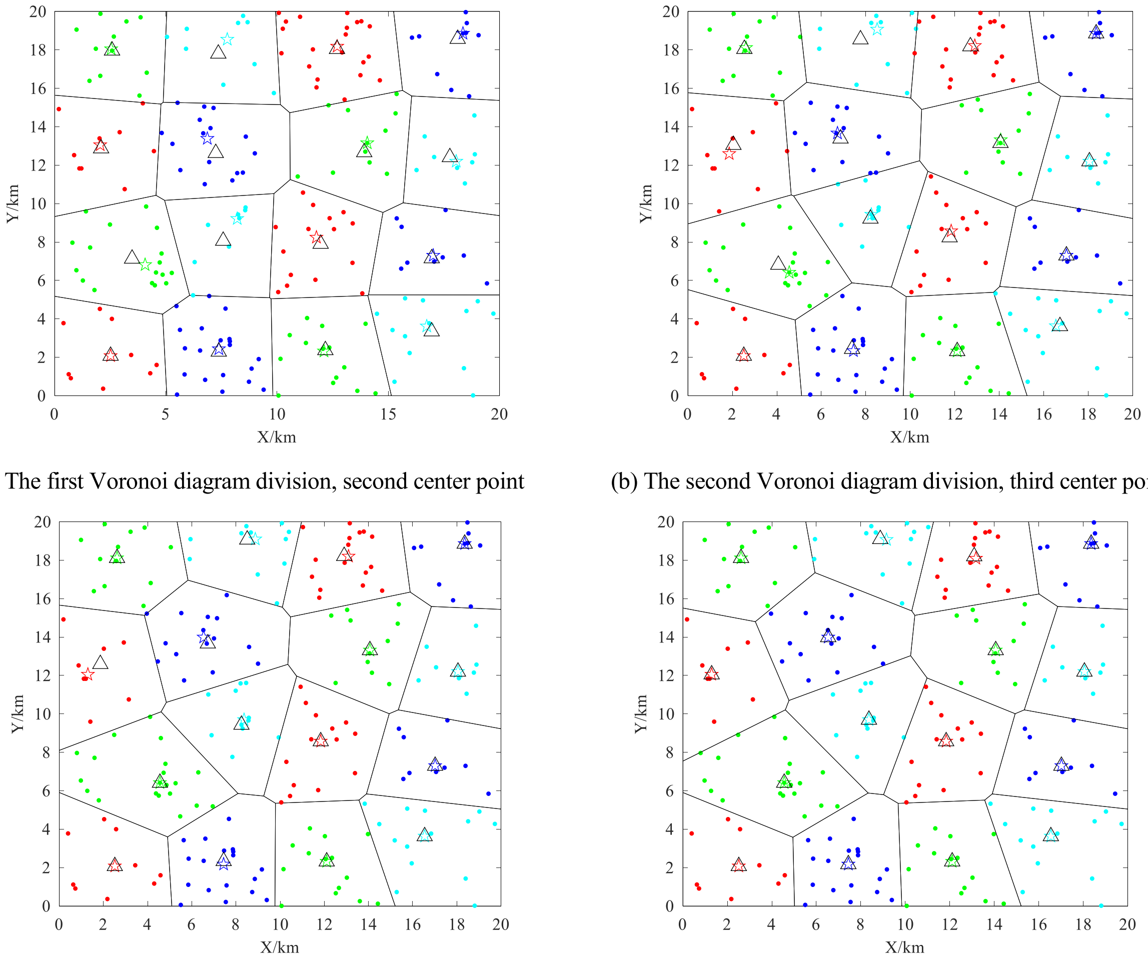
B. ANALYSIS OF SIMULATION RESULTS

1) RELAY COVERAGE ALGORITHM

First, 200 ground user nodes are randomly placed throughout the 20km×20km coverage area. The coverage area is divided into 16 small areas based on the UAV's coverage radius. The first center point is then determined based on the distribution of users in the small areas, as shown in Figures. 8 and 9.

Fig. 8 shows 200 randomly scattered ground users. The same-colored pentagons and users in Fig. 9 represent the calculated first enter point and their coverage relationships, respectively. It is clear that the center of each small area is not where the obtained center points are located, but the place with the shortest sum of distances from all user nodes in the small area. By this method, smaller link transmission delay can be obtained.

The first Voronoi diagram is generated by using the first center point. In the small area of the first Voronoi



(a) The first Voronoi diagram division, second center point

(b) The second Voronoi diagram division, third center point

(c) The third Voronoi diagram division, fourth center point

(d) The fourth Voronoi diagram division, fifth center point

FIGURE 11. The movement of the center points.

diagram, which is seen in Fig. 10(a), the second center point is determined in accordance with the users. The second, third, and fourth Voronoi diagrams as well as the third, fourth, and fifth center points are determined by using the relay coverage algorithm, and the results are displayed in Fig. 10.

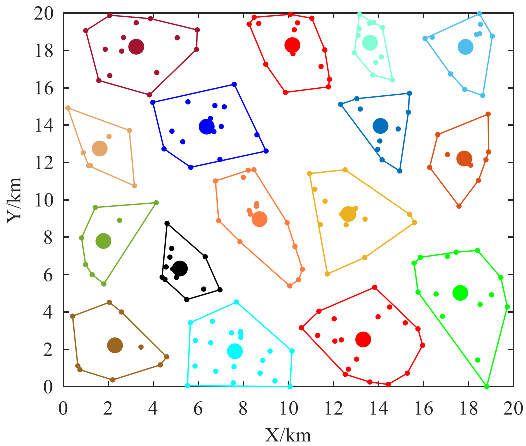
Users are closest to the center point in the small area of the Voronoi diagram, but the distance to all other center points will increase. By gradually reducing the distances between UAV and users, the relay coverage algorithm can gradually reduce the transmission delay of the link to obtain better coverage performance.

The center point movement processes are provided in Fig. 11 to further illustrate the iterative process. The pentagram is the center point deduced this time, while the black triangle stands for the last center point. As can be observed, the center point keeps moving toward the area's dense population of users before finally closing to the ideal position. By doing so, the difference value of the UAVs' relay load keeps dropping until it eventually reaches load balance.

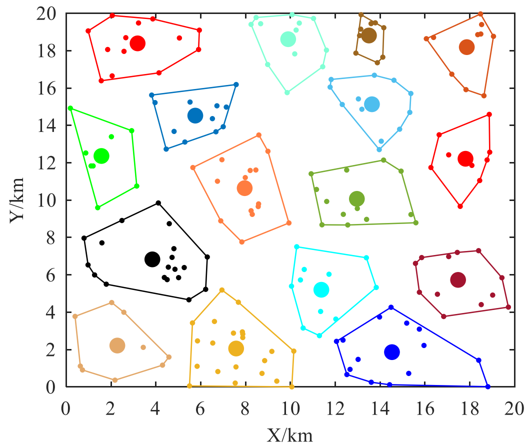
Fig. 12 shows the iterative process of the k-means-based partition method. Considering the distribution of users, UAVs are deployed in places where users are relatively concentrated for relay coverage, which can reduce the link transmission delay to a certain extent.

Fig. 13 shows the relay coverage results based on the CFC method. It can be seen that the main idea of this method is relatively simple. With full coverage of users as the objective, UAVs are deployed at the center of a small area. However, it does not consider the optimization of other performance indexes, which makes the overall performance of relay coverage poor.

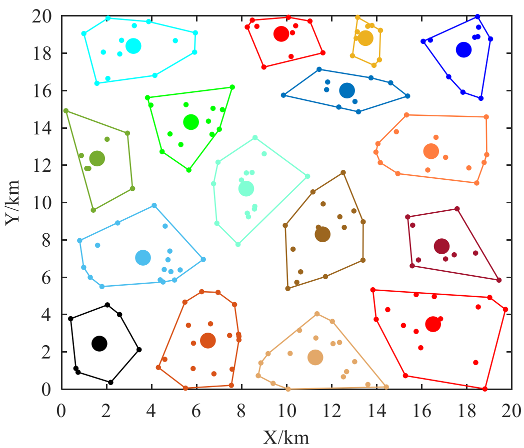
In the iterative process, the comparison results of three methods are showed as Fig. 14. It is clear that the CFC algorithm is less complex and only needs to take the coverage area's sizes and the UAV's radius into account when determining the center point. But it neglects the optimization of load balancing and transmission delay. The performance of the relay network can be slightly enhanced using the k-means partitioning method. Although the proposed relay coverage algorithm is based on the concept



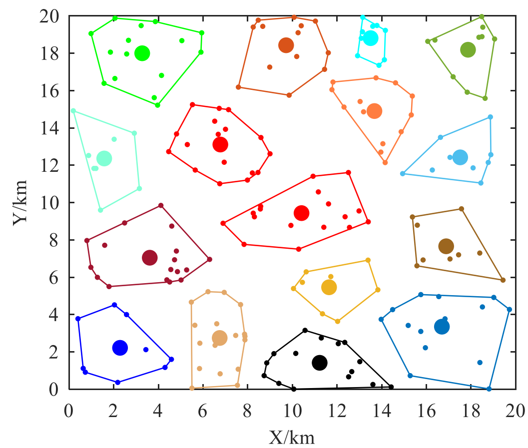
(a) Iteration 1



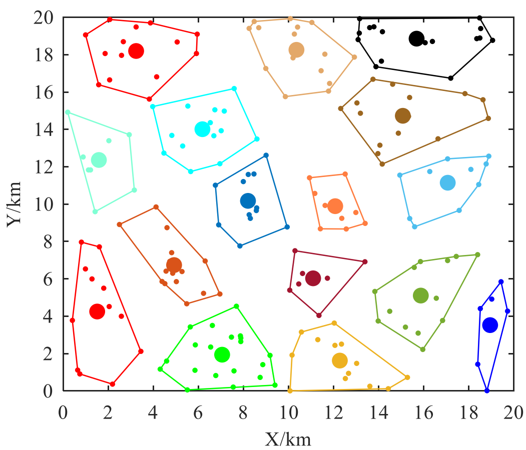
(b) Iteration 2



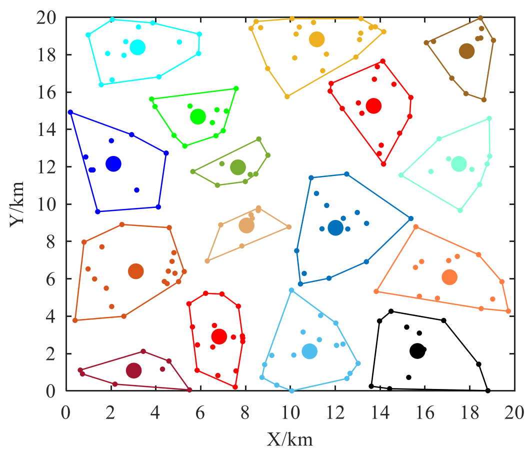
(c) Iteration 3



(d) Iteration 4



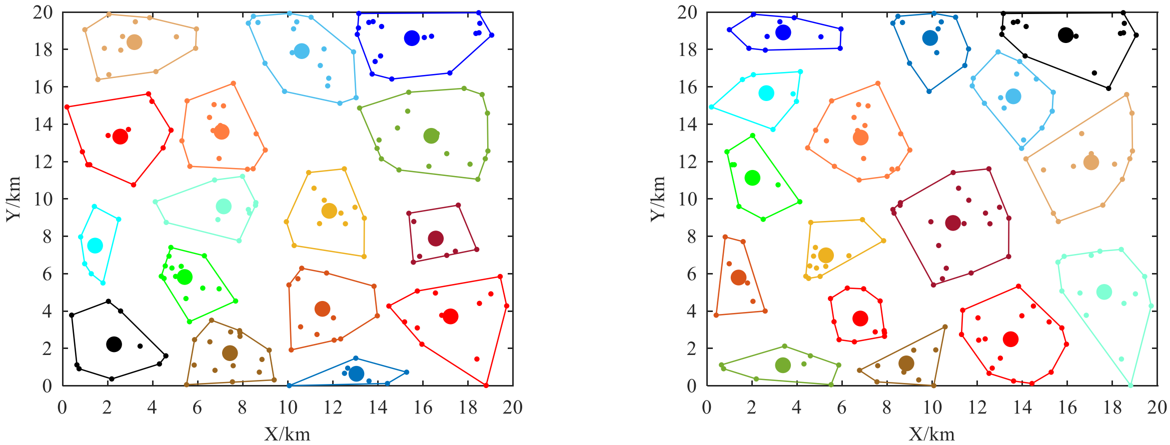
(e) Iteration 5



(f) Iteration 6

FIGURE 12. Iterative process based on k-means partition.

of circular coverage at the initial deployment, it continuously performs iterative optimization using the load balance as the metric in order to balance the UAV's relay load and reduce the transmission delay of the relay network. Finally, the deployment place with the best performance is found by verifying that all users are covered. In general, the proposed algorithm can achieve better relay coverage performance.



(g) Iteration 7 (h) Iteration 8

FIGURE 12. ***(Continued.)*** **Iterative process based on k-means partition.**

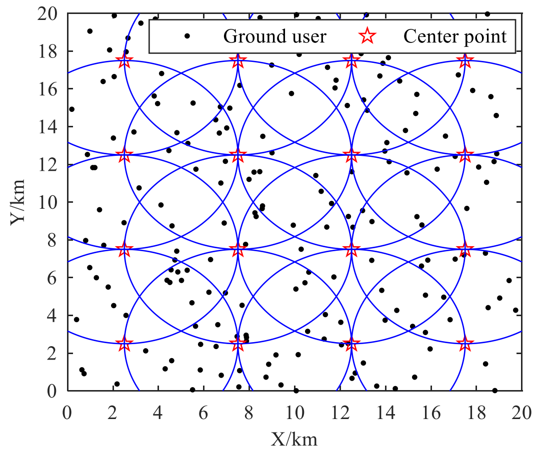


FIGURE 13. **The partition method based on CFC.**

2) RELAY SELECTION STRATEGY

In the relay selection process, the effectiveness of the proposed strategy is evaluated from the viewpoint of throughput. The SNR-based strategy, the distance-based strategy, and the proposed relay selection strategy's performance are compared in Fig. 15.

The proposed relay selection strategy offers improved throughput performance, as evidenced by a bigger proportion of high throughput, a smaller proportion of low throughput, and a higher total throughput, as shown by the cumulative distribution function (CDF). The throughput performance of relay networks is not significantly improved by the distance-based relay selection strategy because it only considers distance as the metric, which with low throughput accounting for a larger proportion, high throughput accounting for a smaller proportion, and poor overall throughput performance. The proposed relay selection strategy has little difference in the improvement of throughput performance compared to the SNR-based strategy. However, when selecting UAV as relay, the proposed strategy considers interference effect generated by neighbouring UAV. As we know, interference is inevitable in communication. Therefore, the proposed strategy is more in line with the actual application scenarios.

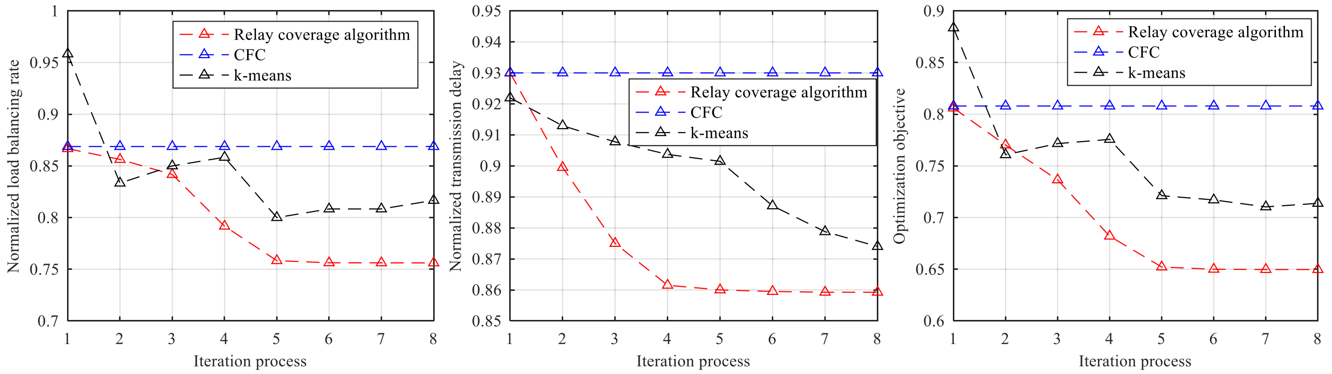
TABLE 2. **Comparison of three forwarding methods.**

Description	The number of relay information λ_k	Processing delay	*SINR*
NAF	More	Less	Less
AF	Less	More	More
HF	Medium	Medium	Medium

3) ANALYSIS OF THREE RELAY FORWARDING METHODS

As can be observed from the forwarding diagrams in Fig. 3 and 4 in Section II, the relay information of each source node is forwarded independently in NAF as opposed to AF and HF, and the UAV node does not merge and package the relay information, which can save processing time. NAF forwards relay information independently while also obviously increasing the number of relay information λ_k, which lowers *SINR*. Additionally, NAF makes for a reduction in the number of source nodes that need to be relayed when the bandwidth is the same. The number of λ_k sent by UAV is reduced as a result of the merging and packaging done by HF and AF, which also improves the *SINR* of relay links. While using the same bandwidth, HF and AF can process the relay information from multiple user nodes within the coverage area at once, lowering queuing delay but increasing processing delay. Table 2 shows the partial performance comparison of the three methods.

A hybrid of NAF and AF is HF. The AF can achieve the best *SINR* of the relay link when the number of source nodes to be relayed is the same, but it also necessitates the longest processing delay. The processing delay in the relay link of NAF is the smallest, but NAF has the worst*SINR*. As a result, the AF can be used in a situation where there is less requirement for delay in order to improve communication quality. The



(a) The variation of load balance rate (b) The variation of the transmission delay (c) The variation of the optimization objective

FIGURE 14. Comparison of three methods.

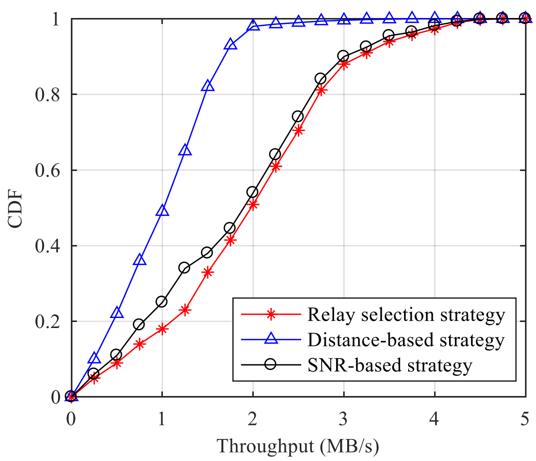


FIGURE 15. The variation of throughput.

biggest number of source nodes can be served by AF at the same time as experiencing the longest processing delay while the transmission bandwidth is the same. The least processing delay, fewest source nodes that can be served simultaneously, and comparable *SINR* of relay links are all characteristics of NAF. The same λ_k is used in relay links, hence the *SINR* is essentially the same. As a result, in the practical case, the network performance requirements can be used to determine the selection of the optimal relay forwarding method.

V. CONCLUSION AND FUTURE NETWORK

In this paper, in order to solve the communication connectivity problem of ground dispersed heterogeneous users, the UAV relay coverage and relay selection subproblems are created from it. The first step is to create a relay coverage algorithm for UAVs in order to find the best deployment placement. This algorithm decreases the transmission delay of the relay link while balancing the relay load on UAVs. A relay selection strategy is then developed. A connection link is established between deployed UAVs with the aim of optimizing relay link throughput while taking various relay forwarding methods into account. Lastly, the processing delay and *SINR* of the relay link performance metrics for each of the three relay forwarding methods are qualitatively compared. Through the comparison of simulated experiments, the results indicate how effective the suggested relay coverage algorithm and relay selection strategy are.

For the future work, there are still a number of important issues that remain to be completed. The next two aspects are just a few examples of important issues. On the one hand, considering the various communication requirements of heterogeneous users, the suitable method of resource allocation can be created to maximize the efficiency of relay networks. On the other hand, considering the dynamic relay scenario with fixed wing UAVs, the optimum relay trajectory should be designed to enhance relay performance. Further research can be carried out on the applicable scenarios of the three different relay information forwarding methods, and the effectiveness of the proposed methods can be verified in more real scenarios.

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