Optimization Method of Relay Network Deployment Using Multi-UAV for Emergency Communication

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Abstract. The unique advantages of UAV with good maneuverability, ease of deployment and control can effectively meet the needs of emergency communications network construction. In order to solve the problem of effective communication security in large-area rescue areas, the idea of using multiple UAVs to construct an emergency relay network was proposed. Under the given mission area, the deployment of this network was studied. First of all, in order to fit the practical application, consider the channel fading to model the UAV coverage area, and propose a UAV relay network model based on connectivity probability. Then, according to the needs of emergency communication scenarios, from the perspective of simplifying the algorithm time complexity and guaranteeing the accuracy of the solution, an algorithm based on simulated annealing for deployment of UAV relay network is proposed. The simulation results show that the proposed algorithm has strong effectiveness and stability and can be applied to the deployment of UAV relay network in the context of emergency communications.

1. Introduction

In recent years, with the development of technology, uavs have greatly improved in terms of flight altitude, endurance time and load capacity. UAVs have the unique advantages of good maneuverability, low cost, ease of deployment and control, flexible communication networking, and easy updating of communication devices (e.g. [1], [2]). As an aerial platform, UAVs can be used to build an emergency communication relay network. Following the link, the user's communication coverage in the task area is achieved. Unlike previous missions that use a small number of uavs to complete single-hop or multi-hop relay missions, under large-scale disaster scenarios such as earthquakes and tsunamis, multiple uavs are needed to achieve effective communication protection for the entire rescue area. Emergency communications relay networks, and the current research in this area is less [3]. In commercial applications, at the Mobile World Congress in 2017, China Mobile and Huawei have cooperated to launch a tandem unmanned aircraft emergency communication high-altitude base station. This kind of uav base station can be quickly lifted into space within 5 minutes to solve the coverage radius of dozens. The 4G signal coverage problem within kilometers [4]. From a practical point of view, the use of multiple uavs to build a large-scale emergency relay network is still in the exploratory phase. There are still many theoretical issues that need to be resolved in the form of network, network protocol design, and network planning.

In this paper, according to the actual application scenario, the idea of using relay UAV to construct emergency communication network is proposed, and the deployment of relay network is studied. This paper is organized as follows. In paper Section II we review related work. In Section III we formulate
the problem. A random deployment algorithm based on SA is designed in Section IV. In Section V we evaluate the algorithms via simulation. We summarize the results in Section VI.

2. Scenes and Modeling

Under normal circumstances, the coverage area of the relay UAV is determined by the altitude of the flight, the height of the coverage area and the maximum propagation distance of the relay signal, and the maximum propagation distance of the relay signal is related to the channel condition of the relay link. A single drone coverage model is shown in Figure 1. Without considering the propagation loss, the paper gives the relational expression of the geometric model of the high altitude UAV relay platform coverage area in [5]. The coverage radius \( r \) is

\[
 r = \sqrt{\frac{R(d^2 - h^2)}{R + h}} \tag{1}
\]

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Among them, \( R \) is the radius of the earth, the height of the UAV is \( h \), and the distance traveled by the relay signal.

**Figure 1.** a relay UAV coverage model

**Figure 2.** UAV relay network model

It can be seen from formula (1) that the coverage radius is related to the propagation distance of the relay signal, and the wireless signal propagation process is usually affected by three factors: path loss, multipath fading and shadow fading, resulting in maximum propagation of the relay link. The distance is usually uncertain. The UAV relay link signal attenuation model can be expressed as:

\[
 L_f = (4\pi d/\lambda)^2 L_s L_m \tag{2}
\]

In the formula: , respectively, the path loss based on the shadow and multipath random fading. According to the literature [6], the composite fading distribution of the fade propagation of the UAV relay link is:

\[
 f_{L_f}(l) = \int_0^\infty f_{L_s}(l|x)f_{L_m}(x|\mu_0)dx = \frac{2}{\Gamma(m)\Gamma(m_f)} \left[ \frac{mm_s}{(4\pi d/\lambda)^2} \right]^{m+m_f-2} l^{-2} \cdot K_{m-m_f} \left[ 2 \frac{mm_s}{(4\pi d/\lambda)^2} l \right], l > 0 \tag{3}
\]

Affected by propagation loss, the connectivity between the user and the relay node is indefinite and presents a probability distribution. Define the connectivity of ground users and relay nodes:

\[
 P_{\text{con}} = \int_0^{A/J_0} f_{L_f}(l)dl = F_{L_f}(d) \bigg|_{l=A/J_0} \tag{4}
\]
In the formula: \( P_t \) transmit power; \( G_t \) transmission antenna gain; \( \Delta L \) extraordinary weather such as atmospheric refraction, rain fade, polarization, feeder loss and other factors; \( F_{l}(d,l) \) to accumulate the probability density function for compound fading, substituting it into formula (4) yields:

\[
d_{\text{max}} = F_{l}^{-1} \cdot P_{\text{con}}
\]  

(5)

Substituting equation (5) into equation (1) yields the relationship between the connectivity probability and the coverage radius as:

\[
P_{\text{con}} = \frac{1}{F_{l}^{-1}} \sqrt{\frac{\Delta^{2} (R + h)}{R} + h_{i}^{2}}
\]  

(6)

The research in this paper is to build a scenario for emergency communications networks under large-scale disaster areas such as earthquakes and tsunamis. To study the convenience of the problem, it is assumed that all users are at the same altitude above ground, and the task area covered by the relay network is \( M \in R^2 \). In order to effectively evaluate the coverage performance of the relay network, the discretization method is used to divide the mission area into discrete points with equal spacing \( M' \subset M \). The total number of discrete points is \(|M'|\). The distance between adjacent discrete points is determined by the accuracy of the problem to be solved. Taking into account the different user density in different locations of the mission area, resulting in different network coverage requirements, set the weight of each discrete point \( p \ (0 \leq p \leq 1) \), It represents the size of the user density near the discrete point. Figure 2 shows the UAV relay network schematic.

Assume that the relay UAV node set is \( U = \{u_{i} \mid i = 1,2,\ldots,n\} \), \( n \) is the number of relay UAV, One relay UAV node in three-dimensional space \( u_{i}(x_{i},y_{i},z_{i}) \). Then according to formula (6), any discrete point in the task area \( m(x,y) \). The probability of connectivity with this UAV is:

\[
P_{m} = \frac{1}{F_{l}^{-1}} \sqrt{\frac{d(u_{i},m)^{2} (R + h)}{R} + z_{i}^{2}}
\]  

(7)

\( d(u_{i},m) = \sqrt{(x - x_{i})^{2} + (y - y_{i})^{2}} \) indicates the coverage radius of the relay UAV to the discrete point \( m \), \( z_{i} \) is the height of the UAV. Assume that there are \( n \) relay nodes in the network, and the connectivity rate between \( m \) and these \( n \) UAV is \( P_{m_{1}}, P_{m_{2}}, \ldots, P_{m_{n}} \), the probability of defining the location of point \( m \) to connect to the relay network is:

\[
P_{\text{con}}(m) = 1 - \prod_{i=1}^{n}(1 - P_{m_{i}})
\]  

(8)

**Definition 1.** Effective coverage point: when \( P_{\text{con}}(m) \geq P_{\text{con}}(th) \) call this point a valid coverage point, denoted as \( N(x,y) \).

\[
R_{\text{area}}(U) = \sum_{x=1}^{M} \sum_{y=1}^{M} P(x,y) \cdot N(x,y)(U)
\]  

(9)

The relay node coverage model shown in Equation (9) is often referred to as a probability coverage model. Compared with the traditional geometric model with constant coverage radius, the probability coverage model has more realistic characteristics. However, in the relay network deployment process, the probability coverage model is more complex than the geometric coverage model, and it is often difficult to adopt the geometric analysis method. Solve the optimal deployment location of relay nodes.

### 3. Random Deployment Algorithm Design

In the solving of the UAV relay network coverage optimization problem, the vector formed \( U = \{u_{i} \mid i = 1,2,\ldots,n\} \) by the position of the relay node set is used as the input parameter of the SA algorithm, and the area of the network effective coverage area is used as the optimization target.
three-dimensional plane, randomly deploy \( n \) relay nodes, the search space dimension of the algorithm \( q = 3n \), the population position vector can be expressed as \( X_i = (x_{i1}, y_{i1}, z_{i1}, x_{i2}, \ldots, z_{in}) \). Each element is in turn represented by the x-axis, y-axis, and z-axis coordinates of the relay node.

Although there is no doubt about the ability of SA[7], it is guaranteed by a strict annealing plan. Specifically, it is a sufficiently high initial temperature, a slow annealing speed, a large number of iterations, and a sufficient number of disturbances at the same temperature. Therefore, the efficiency of SA has always been a major obstacle to the practical application of the algorithm. In order to solve the problem of deployment of UAV relay network, aiming at the defects of SA itself, this paper improves on the basis of SA and proposes an algorithm for deployment of UAV relay network based on simulated annealing(RND-ISA). The following key steps:

1) Population individual initialization. The population of individuals in the algorithm is a vector \( X \) consisting of \( q \) elements. The SA algorithm usually adopts a completely random initial population. Although this method can maintain good population diversity, it is easy to generate individuals with poor fitness, which is not conducive to algorithm convergence. Based on the major small discrete points right, the initial population distribution of weight values of several large area, so close to the initial population the right to re-value the larger node can effectively save the original running time of SA algorithm to improve the accuracy.

2) \( Y \) generated neighborhood solutions. In this paper, the elements of the current solution \( X \) are randomly changed during each iteration to obtain the neighborhood solution \( Y \), and each element is selected from the corresponding sub-domain. The neighborhood solution \( Y \) is not only related to the current solution \( X \), but also related to the current temperature \( T \) and the number of iterations \( m \). The large variation of \( Y \) in the initial iteration is beneficial to maintain the diversity of solutions. In the later iterations, the small change of \( Y \) is beneficial to the convergence of the algorithm.

3) Acceptance probability \( P \). The acceptance probability of the PSA algorithm is related to the size of the weight. By controlling the weight, the acceptance probability of a certain target can be increased or decreased. PSA is a probability \( P \) to accept the new solution.

\[
P = \min(1, \prod_{i=1}^{N} \exp(\frac{R_{area}(X) - R_{area}(Y)}{T_i}))
\]

4. Simulation Analysis

This section analyzes the optimization of the algorithm under conditions of moderate shadow fading. The weights of the discrete points are generated by using random parameters. The actual application can be set according to the population density. The distribution of relay nodes is shown in Figure 3. In the area of dotted lines in the figure, disaster relief areas are included. In order to compare the performance of the proposed algorithm, the basic SA algorithm, ant colony algorithm (ACO)[8] and artificial fish school algorithm (IFO) [9] were used in the same simulation experiment environment.

| Algorithm | Coverage | Variance |
|-----------|----------|----------|
| SA        | 91.13%   | 0.0557   |
| CAO       | 93.33%   | 0.0710   |
| IFO       | 92.61%   | 0.0371   |
| RND-ISA   | 96.23%   | 0.0186   |

In order to verify the effectiveness and stability of the proposed algorithm, the optimization of network coverage is compared under the same task area and the number of relay nodes. The experimental results are shown in Table 1. It can be seen from Table 1 that the coverage optimization performance of the proposed algorithm is obviously better than the other three algorithms, and the variance of 50 results is smaller and the stability is higher.

Figure 4 shows the experimental fluctuations of 100 experiments. The exhaustive algorithm [10] (brute force, BF) is used to traverse the search for the combination of all the solutions during the experiment to find the optimal solution, as a comparison to verify the loss of the solution accuracy of
the IPSA algorithm and computational advantage time, a straight line as shown in Figure 4. It can be seen that the accuracy of the improved SA algorithm is obviously higher than that of the basic SA algorithm and is closer to the optimal solution.

Figure 3. Schematic diagram of UAV deployment results

In order to verify the weight of different task regions and discrete points, the effectiveness of the proposed algorithm is proved. Using equal interval method to randomly generate multiple task areas within the area, using discrete points to represent the size of different task areas. The number of identical discrete points is averaged over 50 times to verify that the coverage of the task area changes and calculate time changes.

Figure 5 shows the relationship between the number of discrete points and the network coverage rate and the number of relay nodes. It can be seen from the figure that the greater the number of relay nodes, the higher the network coverage, but it is worth noting that with the relay With the increase in the number of nodes, the change in network coverage is not significant. This shows that selecting a suitable number of relay uavs for a given mission area is of great significance for optimizing network coverage performance, blindly increasing the number of uavs does not effectively increase network coverage.

Figure 6 shows the comparison of the calculation time at discrete points. It can be seen that as the task area increases, the calculation time of the four algorithms is increasing. The calculation time of the RND-ISA algorithm is much shorter than that of the CAO and IFO algorithms. When the number of discrete points is 120 or more, the average calculation of the RND-ISA is performed. The time is about three times that of the algorithm in this paper. By comparison, the proposed algorithm is more applicable to the deployment of relay networks in emergency communication scenarios.

Figure 4. 100 independent experimental results

Figure 5. Schematic diagram of coverage changes

Figure 6. Schematic diagram of calculation time
5. Summary
In this paper, based on the background of relay network construction in disaster rescue scenarios, this paper proposes an emergency communications-oriented UAV relay network and studies the deployment of the network. From the perspective of practical application, a high altitude relay uav coverage model based on connectivity probability is proposed. From the scene requirements, an SA-based UAV relay network deployment algorithm is designed. The simulation results show that the algorithm has strong effectiveness and stability, and is more suitable for deployment of UAV relay networks in the context of emergency communications.

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