Joint Optimization Method of User Association and Spectrum Allocation for Multi-UAV-Assisted Communication

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Abstract. *In this paper, we mainly study the scenario where multiple UAVs act as aerial base stations (BSs) to provide communication services for ground users (GUs). We propose a method to optimize the max-min average rate of GUs in order to ensure the fairness of user communication, where spectrum reuse and co-channel interference management are considered. The mathematical model is a mixed integer non-linear programming (MINLP) problem which we solve by using the alternating optimization approach where we iteratively optimize the user association, sub-channel allocation and power allocation until convergence. We propose a heuristic algorithm to solve the user association sub-problem and use genetic algorithm (GA) to solve the sub-channel allocation sub-problem. Moreover, the geometric programming algorithm is used to convexify the non-convex power allocation sub-problem and CVX is used to solve it. Simulation results show that the proposed method can effectively improve the transmission rate and ensure the fairness of user communication.*

Keywords

UAV, spectrum reuse, mixed integer non-linear programming, user association, sub-channel allocation, power allocation

1. Introduction

In recent years, UAVs have become a promising application in wireless communication networks due to their high flexibility, on-demand deployment capabilities, and good link characteristics with the ground [1], [2]. For example, UAVs can be rapidly deployed as air base stations or air mobile relays and provide enhanced communication performance for existing wireless communication networks, or support emergency services in war and disaster areas. In addition, UAVs can also be used to perform remote monitoring and transmit real-time video data to ground terminals [3].

1.1 Related Works

Although more research achievements have been made in the field of UAV communication, it still faces many challenges, such as association between UAVs and users, and spectrum resource allocation in one UAV cluster. Nowadays, scholars have carried out a lot of research on the above challenges. In [4], the authors jointly optimized user association and UAV location to maximize the total rate of users' downlink. Since the optimization problem was a mixed integer non-convex optimization problem, the authors decomposed it into an integer user association problem and a non-convex UAV position optimization problem, and then alternately iterated to obtain the suboptimal solution. In [5], aiming at maximizing the minimum average rate of ground users, the problem of UAV flight path and continuous bandwidth allocation was studied, and the relative optimal solution of the problem was obtained by using the alternating optimization technique. In [6], with the goal of maximizing the minimum transmission rate of users, the authors considered the joint optimization of sub-channel allocation and UAV trajectory control, and adopted the alternate optimization method until a relative optimal solution was obtained. However, the above work only considered the resource allocation and UAV deployment optimization of single UAV scene, and there was no spectrum reuse and co-channel interference. In [7], the authors considered the co-channel interference, and optimized the transmission power and sub-channel allocation jointly to maximize the energy efficiency of the system. However, it only studied the wireless network problem with one UAV and one jammer.

For multiple UAV scenarios, in [8], the authors considered co-channel interference, and used a joint algorithm to iteratively optimize sub-channel allocation and UAV speed to maximize the sum rate of UAV uplinks under fixed trajectory conditions, but they didn't consider user association and power allocation. In [9], the authors jointly optimized the sub-channel allocation and power allocation in the multi-cell network considering co-channel interference, and the throughput was used as the performance

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optimization index. But they used distributed optimization to solve the sub-channel allocation, which decomposed the multi-cell optimization problem to single-cell optimization problem, and then multiple cells were iteratively optimized until convergence, but this solution ignored the coordination ability between different cells.

1.2 Contribution and Structure

In view of the above challenges and deficiencies faced by dynamic spectrum allocation under the current multi-UAV-assisted communication, this paper proposes a joint optimization method of user association and spectrum allocation, in order to ensure the fairness of user communication and effectively improve ground user minimum average transmission rate. Compared with existing research, the main contributions of this paper are as follows:

(1) We construct a scenario where multiple UAVs are used as temporary base stations to assist user communication and introduce a more accurate probabilistic line-of-sight channel model. In order to ensure the fairness of user communication, we propose a method to optimize the max-min average rate of GUs where spectrum reuse and co-channel interference management are considered. The method decomposes the mixed integer non-linear programming problem (MINLP) into multiple sub-problems and solves it from three aspects: user association, sub-channel allocation and power allocation, then we can obtain a relatively optimal solution of the original problem.

(2) We solve the problem using an alternate optimization method, which iteratively optimize the user association, sub-channel allocation and power allocation until convergence. Specifically, we develop a heuristic algorithm to solve the user association sub-problem. As for the sub-channel allocation sub-problem, we use a genetic algorithm (GA) to solve it, and an elite retention strategy is introduced to ensure that the best individuals are kept during each evolutionary. Given the UAV-GU association and sub-channel assignment solutions, the power optimization sub-problem is a difficult non-convex problem. So we propose to use the geometric programming [10] algorithm to convexify and use CVX [11] to solve this sub-problem.

(3) Based on the analysis of the convergence and complexity of the proposed algorithm, we prove that the proposed algorithm can effectively improve the transmission rate of users and ensure the fairness of user communication.

The remainder of this paper is organized as follows. In Sec. 2, we present the system model and problem formulation. In Sec. 3, we describe how we solve the three sub-problems and provide the convergence and complexity analysis of the proposed method. Section 4 shows the simulation results and discussion. Finally, Section 5 concludes this work.

2. System Model and Problem Formulation

2.1 System Model

As shown in Fig. 1, we consider the scenarios which deploy multi-UAVs as temporary base stations to provide communication services for multiple temporary hotspots, where spectrum-dependent systems (SDS) are densely distributed, to relieve the pressure on ground base stations. For example, a large-scale sports meeting needs to be held in a stadium in the center of the city. The ground base station can't meet the high traffic demand in such a hot spot, and the cost of building a new ground base station for temporary needs is too high. Therefore, deploying a UAV-based station is a reasonable solution. We consider the downlink UAV-assisted network consisting of a set of $\mathcal{M}=\{1,2,\dots,M\}$ of M UAVs, a set of $\mathcal{K}=\{1,2,\dots,K\}$ of K GUs and a set of $\mathcal{N}=\{1,2,\dots,N\}$ of N sub-channels, which satisfies $M<K$. Considering that there is a control center at the far end of the air to manage the centralized spectrum resources of the UAVs, the UAVs fly at a fixed altitude H during the flight period. To facilitate modeling of problems, we use the time discretization method that the whole flight period is divided into multiple time slots $\mathcal{T}=\{1,2,\dots,T\}$. Because the interval of each time slot is small enough, the trajectory of UAV can be approximately represented as a discrete combination of UAV positions of each time slot. The locations of the UAV $m\in\mathcal{M}$ and the GU $k\in\mathcal{K}$ are denoted as $\mathbf{q}_{\mathrm{U}m}[t]=(x_{\mathrm{U}m}[t],y_{\mathrm{U}m}[t],H)$ and $\mathbf{q}_k=(x_k,y_k)$. Specifically, to make the formula expression clearer, the subscript U in this paper represents UAV.

Besides, UAVs use the orthogonal frequency division multiple access technology to provide services for ground users, which means that users of different sub-channels will not generate interference. At the same time, we consider that for any given UAV, one sub-channel can only serve one GU, while for multi-UAVs, one sub-channel can serve different users, which leads to co-channel interference.

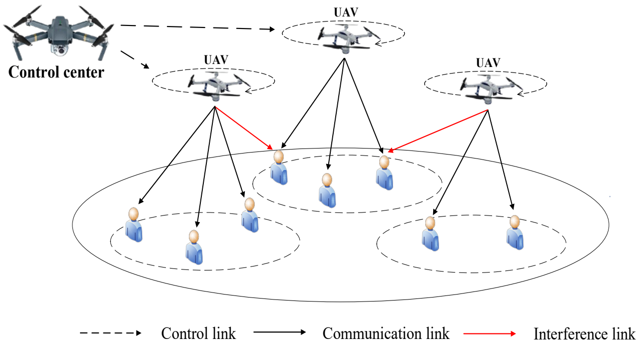

Fig. 1. Multi-UAV-assisted communication network.

2.2 UAV-GU Association

Given the locations of the UAVs in each time slot, GUs need to be associated with the UAVs for high-quality communications. Specifically, GUs should be clustered according to the number of UAVs, and the cluster head UAV will provide communication services for all users in the cluster. The corresponding decision variables are defined as:

$$\omega_{m,k}[t]=\begin{cases}1, & \text{if GU } k \text{ is assigned to UAV } m \\ & \text{in time slot } t \\ 0, & \text{otherwise}\end{cases} . \quad (1)$$

In order to ensure the continuous communication of users, GUs must have one and only one UAV to provide services in each time slot, hence, there are constraints:

$$\sum_{m=1}^{M}\omega_{m,k}[t]=1,\forall k,t . \quad (2)$$

2.3 Sub-channel Allocation

Secondly, we need to determine the sub-channel allocation for each GU, assuming that the sub-channel bandwidth is B, the corresponding decision variable is defined as:

$$b_{k,n}[t]=\begin{cases}1, & \text{if sub-channel } n \text{ is assigned to GU } k \\ & \text{in time slot } t \\ 0, & \text{otherwise}\end{cases} . \quad (3)$$

Since the UAV serves GUs using orthogonal frequency division multiple access (OFDMA) technology, its communication link can occupy multiple sub-channels. At the same time, in order to ensure the continuous communication of users, in each time slot one GU occupies at least one sub-channel, and no more than N sub-channels. There are constraints:

$$1\le\sum_{n=1}^{N}b_{k,n}[t]\le N,\forall k . \quad (4)$$

At the same time, there are constraints that for any given UAV, one sub-channel can only serve one GU, which leads to the coupling between the UAV-GU association matrix and the sub-channel allocation matrix, which is expressed as:

$$\sum_{k=1}^{K}\omega_{m,k}[t]b_{k,n}[t]\le 1,\forall m,n,t . \quad (5)$$

2.4 Power Allocation

When the UAV m is assigned to serve the GU k, its communication link can occupy multiple sub-channels for transmission with different power. The transmission power of the UAV m on the sub-channel n in the time slot t is expressed as $P_{m,n}[t]$. The transmit power of the UAV m in all sub-channels doesn't exceed the upper limit of its own transmit power, which is expressed as:

$$\sum_{n=1}^{N}\sum_{k=1}^{K}\omega_{m,k}b_{k,n}P_{m,n}\le P_m^{\max},\forall m . \quad (6)$$

2.5 Communication Model

In the air-to-ground communications [12], the path loss link is a weighted combination of line-of-sight (LoS) and the non-LoS (NLoS) links by using the standard log-normal shadowing model. The LoS and NLoS path losses $L_{\mathrm{U}m,k}[t]$ in time slot t between UAV m and GU k can be expressed as:

$$L_{\mathrm{U}m,k}[t]=\begin{cases}\xi_{\mathrm{LoS}}\left(4\pi f_{\mathrm{c}}d_{\mathrm{U}m,k}[t]/c\right)^{\alpha}, & \text{LoS link}\\ \xi_{\mathrm{NLoS}}\left(4\pi f_{\mathrm{c}}d_{\mathrm{U}m,k}[t]/c\right)^{\alpha}, & \text{NLoS link}\end{cases} \quad (7)$$

where f_{c} and c are the carrier frequency and the speed of light. ξ_{LoS} and ξ_{NLoS} are the mean additional loss for the LoS and NLoS links due to free space propagation loss. α is the path loss exponent, and $d_{\mathrm{U}m,k}[t]$ is the distance between the UAV m and the GU k, which can be expressed as $d_{\mathrm{U}m,k}[t]=\left\|\mathbf{q}_{\mathrm{U}m}[t]-\mathbf{q}_k\right\|$. Then the LoS probability $\mathrm{Pr}_{\mathrm{U}m,k}^{\mathrm{LoS}}[t]$ and the NLoS probability $\mathrm{Pr}_{\mathrm{U}m,k}^{\mathrm{NLoS}}[t]$ are given by:

$$\mathrm{Pr}_{\mathrm{U}m,k}^{\mathrm{LoS}}[t]=\frac{1}{1+a\exp\left[-b\left(\theta_{\mathrm{U}m,k}[t]-a\right)\right]}, \quad (8)$$

$$\theta_{\mathrm{U}m,k}[t]=\frac{180}{\pi}\arcsin\left(\frac{H}{d_{\mathrm{U}m,k}[t]}\right), \quad (9)$$

$$\mathrm{Pr}_{\mathrm{U}m,k}^{\mathrm{NLoS}}[t]=1-\mathrm{Pr}_{\mathrm{U}m,k}^{\mathrm{LoS}}[t] \quad (10)$$

where a and b are constant values [12], which depend on the network environment. $\theta_{\mathrm{U}m,k}[t]$ is the elevation angle from UAV m to GU k in time slot t. H is the altitude of UAV and we assume that UAVs fly at the same altitude in this paper. Hence, the mean probabilistic path loss of the air-to-ground link is the averaged value of LoS and NLoS links, which can be given by:

$$\bar{L}_{\mathrm{U}m,k}[t]=(\mathrm{Pr}_{\mathrm{U}m,k}^{\mathrm{LoS}}[t]\xi_{\mathrm{LoS}}+\mathrm{Pr}_{\mathrm{U}m,k}^{\mathrm{NLoS}}[t]\xi_{\mathrm{NLoS}})\left(Ad_{\mathrm{U}m,k}[t]\right)^{\alpha} \quad (11)$$

where $A=4\pi f_{\mathrm{c}}/c$.

2.6 Problem Formulation

Under the constraints of user association, sub-channel allocation and power allocation, we aim to maximize the minimum average transmission rate of GUs within a period of T by optimizing the UAV-GU association, sub-channel allocation, and power allocation.

According to Shannon's formula, the achievable transmission rate of UAV m serving GU k on sub-channel n in time slot t is:

$$R_{m,k,n}[t]=\omega_{m,k}[t]b_{k,n}[t]B\log_2\left(1+\frac{P_{m,n}[t]h_{\mathrm{U}m,k}[t]}{I_{\mathrm{U}}[t]+N_0}\right) \quad (12)$$

where B is the sub-channel bandwidth, N_0 is the background noise power, $h_{\mathrm{U}m,k}[t]$ is the channel gain between UAV m and the GU k in time slot t, which satisfies $h_{\mathrm{U}m,k}[t] = 1/\bar{L}_{\mathrm{U}m,k}[t]$. $P_{m,n}[t]$ is the transmission power of the UAV m on the sub-channel n in time slot t.

Therefore, the total transmission rate of GU k in time slot t is:

$$R_k[t] = \sum_{m=1}^{M}\sum_{n=1}^{N} R_{m,k,n}[t]\,. \tag{13}$$

The average transmission rate of GU k in T time slots can be expressed as:

$$\begin{aligned}\bar{R}_k &= \frac{1}{T}\sum_{t=1}^{T} R_k[t] \\ &= \frac{1}{T}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N} \omega_{m,k}[t]b_{k,n}[t]B\log_2\left(1+\frac{P_{m,n}[t]h_{\mathrm{U}m,k}[t]}{I_{\mathrm{U}}[t]+N_0}\right).\end{aligned} \tag{14}$$

$I_{\mathrm{U}}[t]$ is the co-channel interference of different UAV-GU clusters, specifically expressed as follows:

$$I_{\mathrm{U}}[t] = \sum_{i=1,i\neq m}^{M}\ \sum_{j=1,j\neq k}^{K} \omega_{i,j}[t]b_{j,n}[t]P_{i,n}[t]h_{\mathrm{U}i,k}[t]\,. \tag{15}$$

Considering user communication fairness, our design goal is to maximize the minimum average transmission rate of all GUs within a period of time T by jointly optimizing the UAV-GU association matrix $\mathbf{W}_{\mathrm{f}}$ (a three-dimensional matrix of $M\times K\times T$ about variable $\omega_{m,k}[t]$), sub-channel allocation matrix $\mathbf{B}_{\mathrm{f}}$ (a three-dimensional matrix of $K\times N\times T$ about variable $b_{k,n}[t]$)and power allocation matrix $\mathbf{P}_{\mathrm{f}}$ (a three-dimensional matrix of $M\times N\times T$ about variable $P_{m,n}[t]$). For the convenience of problem solving, we introduced $\mu(\mathbf{W}_{\mathrm{f}}, \mathbf{B}_{\mathrm{f}}, \mathbf{P}_{\mathrm{f}}) = \min_{k\in\mathcal{K}} \bar{R}_k$ as the minimum rate of all GUs. Then our optimization problem is equivalent to maximization $\mu(\mathbf{W}_{\mathrm{f}}, \mathbf{B}_{\mathrm{f}}, \mathbf{P}_{\mathrm{f}})$. Therefore, the dynamic spectrum allocation objective function for this problem can be expressed as:

$$\begin{aligned}\max_{\mu,\mathbf{W}_{\mathrm{f}},\mathbf{B}_{\mathrm{f}},\mathbf{P}_{\mathrm{f}}}\ & \mu \\ \text{s.t. } & C_1: \bar{R}_k \geq \mu, \forall k, \\ & C_2: \sum_{m=1}^{M}\omega_{m,k}[t] = 1, \forall k,t, \\ & C_3: 1 \leq \sum_{n=1}^{N} b_{k,n}[t] \leq N, \forall k,t, \\ & C_4: \sum_{k=1}^{K}\omega_{m,k}[t]b_{k,n}[t] \leq 1, \forall m,n,t, \\ & C_5: P_{m,n}[t] \geq 0, \forall m,n,t, \\ & C_6: \sum_{n=1}^{N} P_{m,n}[t] \leq P_m^{\max}, \forall m,t, \\ & C_7: \omega_{m,k}[t] \in \{0,1\}, \forall m,k,t, \\ & C_8: b_{k,n}[t] \in \{0,1\}, \forall k,n,t\end{aligned} \tag{16}$$

where C_1 describes that the average transmission rate of any GU in a period of time is larger than the objective function. C_2 describes that one GU can only be served by one UAV in one time slot. C_3 describes that given the UAV m, GU k can transmit in multiple sub-channels, but no more than N sub-channels. C_4 describes that given the UAV m, only one GU can be assigned to one sub-channel. C_5 describes that the power of UAVs is not negative. C_6 describes that the sum of the transmit power of UAVs in all sub-channels doesn't exceed its own maximum transmit power. C_7 describes that the value range of each element in the UAV-GU association matrix is 0 or 1. C_8 describes that the value range of each element in the sub-channel allocation matrix is 0 or 1.

3. Problem Solving

Since the objective function involves binary variables $\omega_{m,k}[t]$, $b_{k,n}[t]$ and real variables $P_{m,n}[t]$, hence the formula (16) is a mixed integer non-linear programming problem (MINLP), so this paper uses the block coordinate descent (BCD) algorithm to solve it, specifically, given the values of other variables in the corresponding sub-problem, iteratively optimize each set of variables until convergence.

3.1 Optimize UAV-GU Association

Given sub-channel allocation and power allocation, optimize the UAV-GU association. Let $\mathbf{B}_{\mathrm{f}}$, $\mathbf{P}_{\mathrm{f}}$ in (16) as fixed variables and let $\mathbf{W}_{\mathrm{f}}$ as decision variables, then the mixed integer non-linear programming problem in (16) is transformed into an integer programming problem which can be described as:

$$\begin{aligned}\max_{\mu,\mathbf{W}_{\mathrm{f}}}\ & \mu \\ \text{s.t. } & C_1, C_2, C_4, C_7.\end{aligned} \tag{17}$$

The integer non-convex optimization problem is difficult to solve, so we propose a heuristic algorithm to solve the UAV-GU association problem. Table 1 gives the specific solution steps of this problem:

```
Algorithm 1 UAV-GU Association Algorithm
Input: sub-channel allocation matrix $\mathbf{B}_{\mathrm{f}}$, power allocation matrix $\mathbf{P}_{\mathrm{f}}$
1. Initialization: Let $r = 0$, initial the UAV-GU association matrix $\mathbf{W}_{\mathrm{f}}$ which satisfies the problem (17);
2. Repeat
3.   $r = r + 1$;
4.   Calculate the minimum average transmission rate $\mu$ over the period of time $T$ and find its corresponding users $k_{\min}$;
5.   Time slot $t$ repeats from 1 to $T$;
6.     UAV $m$ repeats from 1 to $M$;
7.       Calculate the average transmission rate $\mu(m)$ of $M$ UAVs serving user $k_{\min}$ respectively, among $m \in \mathcal{M}$, then we assign the UAV $m'$ with the largest average transmission rate to the user, which satisfies $m' = \arg\max(\mu(m))$;
8.       Calculate the minimum average transmission rate $\mu$ over a period of time $T$ again, and find its corresponding user $k'_{\min}$;
         If $k'_{\min} = k_{\min}$, end the loop; otherwise, let $k_{\min} = k'_{\min}$, return to step 5;
9. Update $\mathbf{W}_{\mathrm{f}}$;
10. Until convergence: $\mu$ isn't increasing
Output: $\mu^*, \mathbf{W}_{\mathrm{f}}^*$
```

Tab. 1. UAV-GU association algorithm.

3.2 Optimize Sub-channel Allocation

Given UAV-GU association and power allocation, optimize the sub-channel allocation strategy. Let $\mathbf{W}_\mathrm{f}$, $\mathbf{P}_\mathrm{f}$ in (16) as fixed variables and let $\mathbf{B}_\mathrm{f}$ as decision variables, then the mixed integer nonlinear programming problem in (16) is transformed into an integer programming problem, which can be described as:

$$\begin{aligned} &\max_{\mu,\mathbf{B}_\mathrm{f}} \ \mu \\ &\text{s.t. } \ C_1, C_3, C_4, C_8. \end{aligned} \tag{18}$$

The integer non-convex optimization problem is difficult to solve, so we propose a sub-channel allocation algorithm based on GA. Table 2 gives the specific solution steps and key steps of the algorithm:

The key steps are described as following:

(1) Gene encoding: First, perform gene straightening on the sub-channel allocation matrix $\mathbf{B}_\mathrm{f}$, that is, convert the $K \times N \times T$ matrix into $1 \times KNT$ matrix, then let it as an individual in the population;

(2) Initial population: randomly generate a two-dimensional matrix of $\lambda \times KNT$, where λ is the number of individuals in the population;

(3) Gene crossover: The λ individuals in the population are paired in a random manner to form $\lambda/2$ paired genome, and then the two genes in one paired genome are crossed. In this paper, we adopt the single-point crossover method, that is, according to a given crossover probability p_c, each other's genes are exchanged at the crossover point, thereby generating a new encoding vector.

(4) Gene mutation: In order to optimize the local search ability, maintain the diversity of the population in the process of finding the optimal solution and prevent premature convergence. That is, according to the given mutation probability p_m, the value of one or more mutation points in the gene is reversed to generate a new encoding vector.

Algorithm 2 GA-based Sub-channel Allocation Algorithm

```
Input: UAV-GU association matrix $\mathbf{W}_\mathrm{f}$, power allocation matrix $\mathbf{P}_\mathrm{f}$
1. Initialization: Let $r = 0$, initial the sub-channel allocation matrix which satisfies the problem (18), and randomly generate the initial population
2. Repeat:
3.    $r = r + 1$;
4.    In order to ensure the diversity of the population, we perform the gene crossover and gene mutation operations to generate new individuals;
5.    In order to prevent the generation of multiple unqualified individuals after step 4, we perform gene correction and gene screening operations;
6.    Calculate the fitness of individuals in the population according to the fitness function, then select according to the roulette strategy, in order to control the number of populations to be the initial population number, and retain the optimal individual;
7. When the algorithm execution reaches the preset algebra, end; otherwise return to the loop;
Output: $\mathbf{B}_\mathrm{f}^*$
```

Tab. 2. GA-based sub-channel allocation algorithm.

(5) Gene correction and gene screening: Before selecting individuals in the population, correct and screen the individuals that have undergone gene crossover and mutation in each time slot according to the constraints in (18), in order to prevent too many genetic individuals that doesn't meet the conditions.

(6) Fitness function: The fitness function represents the adaptive ability of individuals in the population, and equation (18) is the optimization objective in this algorithm.

(7) Selection strategy: The selection strategy used here is the roulette selection method. It is based on the size of the individual fitness. If the individual fitness value is small, it is likely to be discarded; if the individual fitness value is large, it is more likely to be selected. Through the selection strategy, the population number is controlled at the initial population number. At the same time, in order to ensure that the best individuals are not lost in the process of selection and crossover, an elite retention strategy is also introduced in the implementation process of the algorithm, that is, the best individual of each generation is saved to the next generation, which improves the convergence speed of the algorithm.

3.3 Optimize Power Allocation

Given UAV-GU association and sub-channel allocation, optimize power allocation strategy. Let $\mathbf{W}_\mathrm{f}$, $\mathbf{B}_\mathrm{f}$ in (16) as fixed variables and let $\mathbf{P}_\mathrm{f}$ as decision variables, then the mixed integer non-linear programming problem in (16) is transformed into a non-integer programming problem, which can be described as:

$$\begin{aligned} &\max_{\mu,\mathbf{P}_\mathrm{f}} \ \mu \\ &\text{s.t. } \ C_1, C_5, C_6. \end{aligned} \tag{19}$$

It can be seen that the power allocation problem is a non-convex optimization problem, and we can transform it into a convex optimization problem by geometric programming [10].

Theorem 1 The optimization problem in (19) can be transformed into convex form by using logarithmic transformation: $\tilde{P}_{m,n}[t] = \log_2\left(P_{m,n}[t]\right)$.

Prove:

In geometric programming, $\log_2(1 + x)$ can be approximated as $\log_2(x)$ in high SINR regimes in this paper. Use logarithmic variables $\tilde{P}_{m,n}[t] = \log_2(P_{m,n}[t])$, the constraints C_1 can be converted to (20).

It can be seen from (20) that the first term is a linear function of $\tilde{P}_{m,n}[t]$, it can be either convex or concave [12], so we consider it as a concave function for the following convex constraint proof. The second term contains the log-

$$\begin{aligned}
&\frac{1}{T}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}\omega_{m,k}[t]b_{k,n}[t]B\log_2\left(\frac{P_{m,n}[t]h_{\mathrm{U}m,k}[t]}{I_{\mathrm{U}}[t]+N_0}\right)\\
&=\frac{1}{T}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}\omega_{m,k}[t]b_{k,n}[t]B\log_2\left(\frac{P_{m,n}[t]h_{\mathrm{U}m,k}[t]}{\sum\limits_{i=1,i\neq m}^{M}\sum\limits_{j=1,j\neq k}^{K}\omega_{i,j}[t]b_{j,n}[t]P_{i,n}[t]h_{\mathrm{U}i,k}[t]+N_0}\right)\\
&=\frac{1}{T}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}\omega_{m,k}[t]b_{k,n}[t]B\log_2\left(\frac{\exp\tilde{P}_{m,n}[t]h_{\mathrm{U}m,k}[t]}{\sum\limits_{i=1,i\neq m}^{M}\sum\limits_{j=1,j\neq k}^{K}\omega_{i,j}[t]b_{j,n}[t]\exp\tilde{P}_{i,n}[t]h_{\mathrm{U}i,k}[t]+N_0}\right)\\
&=\frac{1}{T}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}\omega_{m,k}b_{k,n}B(\tilde{P}_{m,n}[t]+\log_2 h_{\mathrm{U}m,k}[t])\\
&\quad-\frac{1}{T}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}\omega_{m,k}[t]b_{k,n}[t]B\log_2\left(\sum_{i=1,i\neq m}^{M}\sum_{j=1,j\neq k}^{K}\omega_{i,j}[t]b_{j,n}[t]\exp\tilde{P}_{i,n}[t]h_{\mathrm{U}i,k}[t]+N_0\right)\geq\mu,
\end{aligned}\tag{20}$$

$$\begin{aligned}
&\max_{\mu,\tilde{\mathbf{P}}_f}\ \mu\\
&\text{s.t.}C_1:\frac{1}{T}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}\omega_{m,k}[t]b_{k,n}[t]B\log_2\left(\sum_{i=1,i\neq m}^{M}\sum_{j=1,j\neq k}^{K}\omega_{i,j}[t]b_{j,n}[t]\exp\tilde{P}_{i,n}[t]h_{\mathrm{U}i,k}[t]+N_0\right)\\
&\qquad+\mu-\frac{1}{T}\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}\omega_{m,k}[t]b_{k,n}[t]B(\tilde{P}_{m,n}[t]+\log_2 h_{\mathrm{U}m,k}[t])\leq\ 0,\forall k\\
&\quad C_6:\sum_{n=1}^{N}\exp\tilde{P}_{m,n}[t]-P_m^{\max}\leq 0.\forall m,t
\end{aligned}\tag{21}$$

sum-exp form, this form is convex [12], and the negation becomes a concave function. Concave function addition is still a concave function, and the expression that concave function greater than a constant is convex constraint, so the constraints C_1 is convex of $\tilde{P}_{m,n}[t]$. The original question turns into (21).

It is easy to know that the constraints are both log-sum-exp and sum-exp, so they are convex constraints. Since the problem is a convex optimization problem, the problem can be solved by applying MATLAB's CVX package to get $\tilde{P}_{m,n}{}^*[t]$, and after that, apply $\tilde{P}_{m,n}[t] = \log_2(P_{m,n}[t])$ again to get $P_{m,n}{}^*[t]$. Its solution (Algorithm 3) is a standard CVX solution algorithm.

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Algorithm 4 A Joint Optimization Method of User Association and Spectrum Allocation
Input: the number of UAVs $M$, the number of GUs $K$, the number of sub-channels $N$
1. Initialization: Let $r = 0$, initialize the allocation matrix ($\mathbf{W}_f$, $\mathbf{B}_f$, $\mathbf{P}_f$) that satisfies the optimization problem
2. Repeat
3.   Given sub-channel allocation and power allocation, solve sub-problem 3.1 by Algorithm 1 to get $\mathbf{W}_f^r$;
4.   Given the UAV-GU association and power allocation, solve sub-problem 3.2 by Algorithm 2 to get $\mathbf{B}_f^r$;
5.   Given the UAV-GU association and sub-channel assignment, solve sub-problem 3.3 by Algorithm 3 to get $\mathbf{P}_f^r$;
6.   Update $r = r + 1$;
7. End: $\mu^{r+1} - \mu^r \leq \zeta$ reach the maximum number of iterations $r_{\max}$, end;
   Otherwise, return to the loop;
Output: $\mu^*, \mathbf{W}_f^*, \mathbf{B}_f^*, \mathbf{P}_f^*$
```

Tab. 3. A joint optimization method of user association and spectrum allocation.

3.4 Joint Optimization Algorithm

Based on the partial results of Sec. 3.1, 3.2, and 3.3, we propose a joint optimization method of user association and spectrum allocation, which is described in Algorithm 4.

Since the optimization result of each sub-problem is incremental, and the transmission rate is the optimization target, there must be an upper limit for its value, so the proposed Algorithm 4 must converge to a feasible solution.

Figure 2 is the schematic flowchart of Algorithm 4.

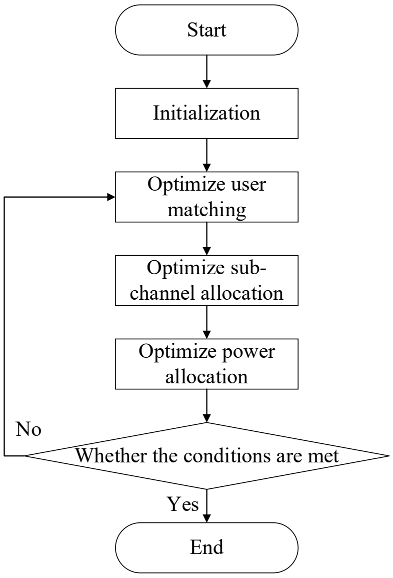

Fig. 2. Algorithm 4 flowchart.

3.5 Complexity Analysis

Next, we analyze the complexity of the proposed algorithm with the required arithmetic. For the UAV-GU association sub-problem, since Algorithm 1 allocates UAVs to each GU, it needs to traverse all UAVs and GUs, hence its complexity is $\mathcal{O}_1(L_1MKT)$, where L_1 is the number of iterations required for Algorithm 1 to converge; for Algorithm 2, the complexity of GA depends on the complexity of its fitness function $\mathcal{O}_{22}(\mu)$, assuming that the maximum number of iterations is Max_GEN, and the number of populations is λ, then the complexity is $\mathcal{O}_2(Max\_GEN \times \lambda \times \mathcal{O}_{22}(\mu))$; for Algorithm 3, it has a complexity of $\mathcal{O}_3(M(N)^{4.5}T\log(1/\zeta))$ [12]. Assuming that L is the number of iterations of Algorithm 4, the complexity of the joint optimization algorithm is $\mathcal{O}(L(\mathcal{O}_1 + \mathcal{O}_2 + \mathcal{O}_3))$.

4. Simulation Results and Discussion

4.1 Parameter Settings

In this section, we evaluate the performance of the proposed algorithm. We consider a circular network area with radius $R_0 = 500$ m with two or more clusters i.e., hotspots, of GUs. The radius of each circular cluster is $R_c = 200$ m and different clusters are placed far enough apart not to overlap. Assuming that each UAV serves a hotspot area, for each hotspot area, firstly, we should determine its center $\mathbf{q}_0 = (x_0, y_0)$ and UAV's uniform circular motion radius R_{UAV}. Given the distribution of GUs in the hotspot area, the center point can be obtained by clustering algorithm, and the uniform circular motion radius can be determined by $R_{\mathrm{UAV}} = \min(d_m^{\max1}, d_m^{\max2})$, where $d_m^{\max1} = vT/2\pi$ represents the largest circumference that UAV can travel during the flight period and $d_m^{\max2} = \max\|\mathbf{q}_k - \mathbf{q}_0\|$, $k \in \mathcal{K}$ represents the maximum distance from GUs to the center point. Assuming that the flight energy of the UAV is sufficient to cover the flight operations and wireless communication within its mission completion time, which is supported in [14], the flight time of a UAV equipped with a 3-cell, 3250 mAh, 11.1 V LiPo battery is approximately 20 minutes.

In order to make the parameter settings more reasonable, we refer to [12], [13] to set the simulation parameters, as shown in Tab. 4.

Parameter	Description	Value
	Terrestrial user distribution	1000×1000 m^2
M	Number of UAVs	[2, 3, 4]
K	Number of GU	[8, 10, 12, 14, 16]
N	Number of sub-channels	[10, 15, 20, 25, 30]
B	Bandwidth of each sub-channel	10 MHz
H	Altitude of UAV	300 m
$P_m^{\max}$	Transmit power of UAV	2 W
ξ_{LoS}	Line-of-sight link loss	3 dB
ξ_{NLoS}	NLOS link loss	23 dB
T	Flight period	20 s
f_c	Carrier frequency	2 GHz
α	Air-Ground Path Loss Index	2
a	Environmental parameters	11.95
b	Environmental parameters	0.136
N_0	Noise power	–170 dBm/Hz
$V_{\max}$	Maximum speed of UAV	40 m/s

Tab. 4. System simulation parameters.

4.2 Simulation Results

Figure 3 shows the location distribution and trajectories of 14 GUs served by 3 UAVs. Figure 4 shows that according to the initial UAV-GU association strategy, the UAVs only serve users in the corresponding hotspot areas. Figure 5 uses $t = 13$ time slot as an example, after the optimization of the joint optimization method proposed in this paper, the service UAVs of 8th GU and 13th GU have changed, which can provide the better service performance.

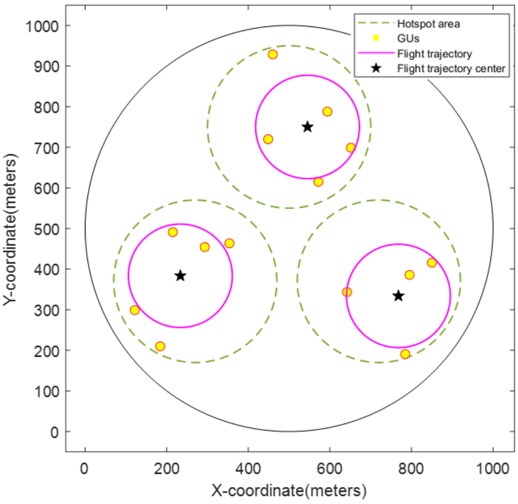

Fig. 3. Location distribution of UAVs and GUs.

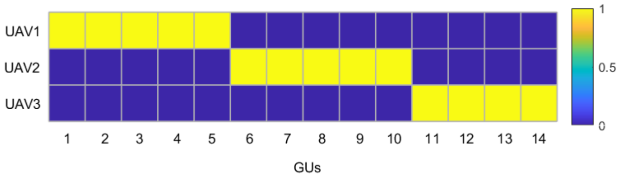

Fig. 4. Initial UAV-GU association matrix.

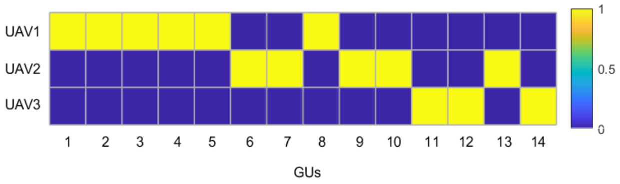

Fig. 5. UAV-GU association matrix with $t = 13$ time slot.

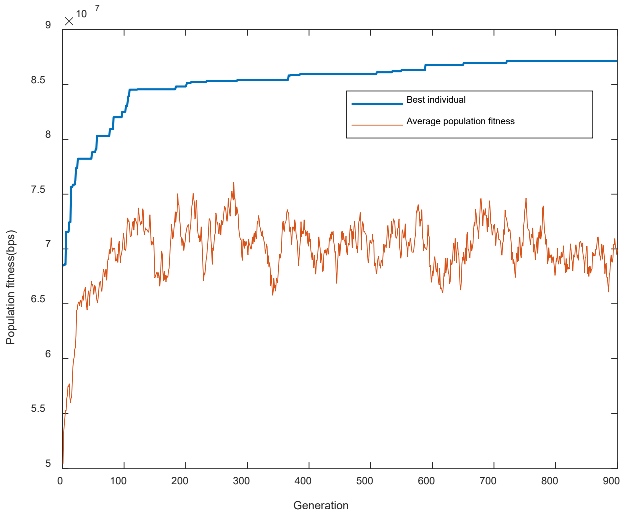

Fig. 6. Convergence diagram of sub-channel allocation based on GA.

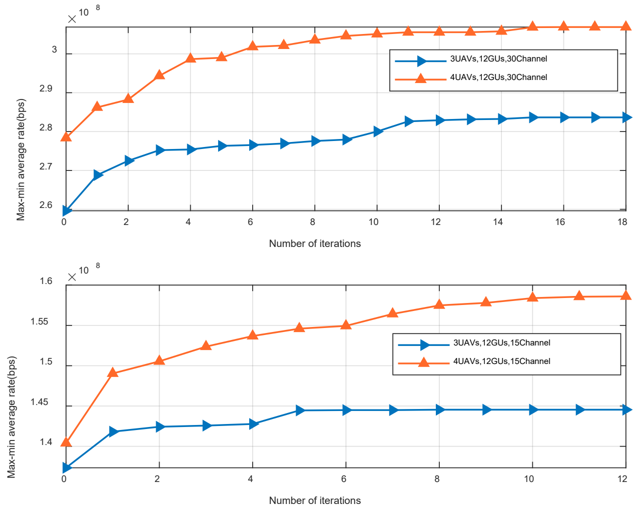

Fig. 7. Convergence diagram of joint optimization algorithm.

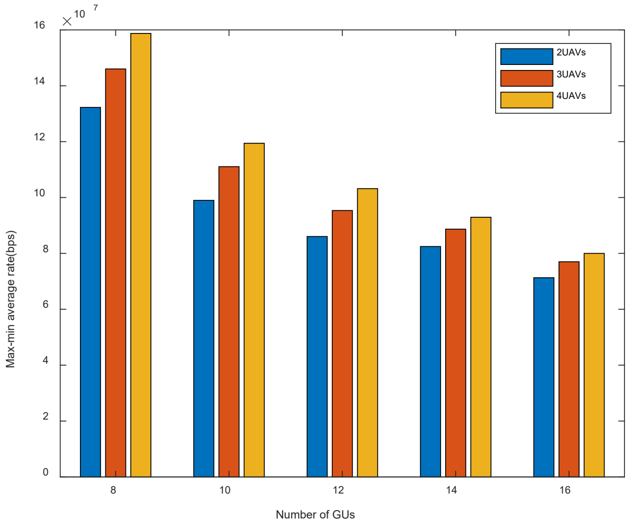

Fig. 8. Max-min rates under different numbers of GUs.

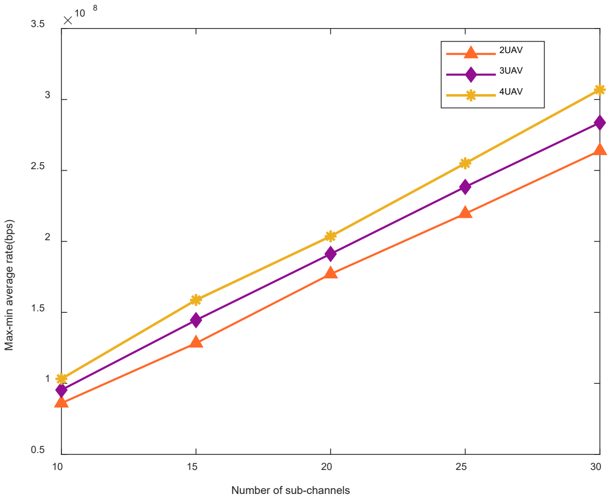

Fig. 9. Max-min rates under different number of sub-channels.

Figure 6 shows the GA-based sub-channel assignment convergence graph for 3 UAVs, 12 GUs, and 10 sub-channels, where the initial population is 100, the maximum number of generations is 900, the crossover probability is 0.95, and the mutation probability is 0.1. The results show that when the evolution reaches 720 generations, the average fitness of the population and the minimum average transmission rate of the GUs is stable.

Figure 7 shows the convergence curves of the joint optimization algorithm proposed in this paper in different scenarios. It can be seen that the value of the objective function increases continuously in the iterative process. At the same time, with the increase of the number of UAVs and the number of sub-channels, the complexity of the joint optimization algorithm and the number of iterations required increases.

Figure 8 shows the comparison of the max-min average rate of users with different numbers of GUs when the number of available sub-channels is 10. The results show that with the increase of the number of GUs, the max-min average rate of users decreases. This is because in order to satisfy the communication requirements, there will be multiple users occupying the same sub-channel, and the co-channel interference will increase. In addition, the more the number of UAVs, the higher the max-min average rate of GUs, this is because the more UAVs, the greater the power that can be allocated to the users, and there are more channel access schemes that can be selected. However, the rate gap between the 3 scenarios decreases when the number of GUs increases due to stronger interference with the larger number of UAVs.

Figure 9 shows the comparison of the max-min average rate for 12 GUs under different number of sub-channels. It can be seen that the max-min average rate of GUs increases almost linearly with the increase of the number of sub-channels. In addition, the more the number of UAVs, the greater the max-min average rate of users, and the difference will become more and more obvious as the number of sub-channels increases.

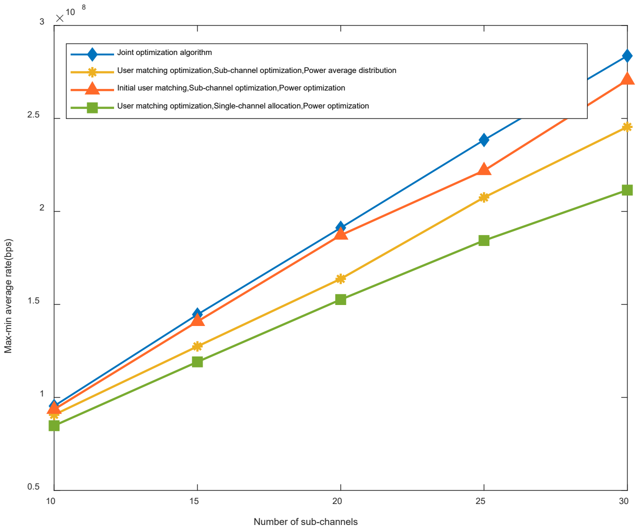

Fig. 10. Performance comparison of different algorithms.

In order to further verify the effectiveness of the proposed algorithm in the multi-UAV assisted communication scenario, we use the method of simulation comparison to analyze the performance of the proposed algorithm by replacing the solving algorithm of one sub-problem in the joint algorithm. The single-channel allocation algorithm [15] performs multiple single-channel access until all available sub-channels are allocated, and uses the maximum weight association algorithm to ensure that the objective function value of the spectrum allocation process for each single-channel access is the largest. Figure 10 shows the performance comparison of the four schemes in the scenario of 3 UAVs and 12 GUs. It can be seen that the performance of the joint optimization algorithm proposed in this paper is better than the other three joint algorithms. The single-channel allocation algorithm can find the optimal channel to access in each selection, but due to its distributed selection characteristics, the co-channel interference between different clusters is not considered, resulting in the worst performance; the power average distribution strategy can't dynamically adjust the power of UAV in each sub-channel, so its performance is lower than the algorithm proposed in this paper.

5. Conclusion

In this paper, we studied the dynamic spectrum allocation problem in the multi-UAV-assisted communication scenario, where UAVs served as air base stations to provide temporary services for GUs with given trajectories. In order to ensure the fairness of user communication, considering spectrum reuse and co-channel interference, aiming at maximizing the minimum average transmission rate of GUs, we proposed a joint optimization method of user association and spectrum allocation to solve the above mixed integer non-linear optimization problem. Specifically, we solved the optimal association problem with an iterative UAV-GU association algorithm, solved the sub-channel allocation with the genetic algorithm, and solved the power allocation with the convex optimization algorithm. The experimental results proved the effectiveness of the algorithm which can greatly improve the user transmission rate and ensure the user communication fairness.

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