A Novel Algorithm of UAV-Mounted Base Station Placement and Frequency Allocation

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Abstract. UAV equipped with base stations have recently gained significant development in cases of the terrestrial base station may not satisfy the communication command. Due to the agility and flexibility of UAV, it is used widely in disaster resilience, scenarios of unexpected and temporary events. Although UAV-mounted base station provides a fast coverage for the terrestrial users, the placement of UAVs is a problem to solve, especially the area to be covered is large which need multi-UAVs to cooperate to provide coverage. The difference of terrestrial and air-to-ground channel makes it a new coverage problem. Besides, the interference from UAVs requires a technique to manage the spectrum. In this paper, we formulate the placement of UAV as a 3-D problem, and then proposed a soft frequency reuse scheme to dynamically manage frequency resource. Simulations results show the algorithm is feasible to operate on resource-limited UAV platforms.

Keywords: Unmanned Aerial Vehicles
Mobile base station placement · User coverage · Soft Frequency Reuse
Spectrum allocation

1 Introduction

With the development of wireless communication, next generation wireless networks are in increasing demand of high reliability and availability. This adoption is motivated by the situations which are unexpected or temporary. Be in a disaster, the fixed infrastructure could be damaged by floods, earthquake or tsunamis, the wireless networks is destroyed, and could hinder the rescue works. Or in battlefields or rural area, it is impossible to invest an infrastructure. In these cases, utilizing unmanned aerial vehicles (UAVs) is a feasible solution for realizing wireless networks. However, how to place a UAV-mounted base station to benefit and assist the network on the ground at most is one of the biggest challenges.

Although there have been amounts of works on UAV-aided networks, the placement of UAV-mounted base station is still at its infancy. The authors in [1] uses p UAVs to serve terrestrial users, which the capacity of the each UAV is constrained. They use K-means to partition the terrestrial users to be served by

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the UAVs, the other unsupported users are served by fixed base stations. In [2], an algorithm of offload as many users as possible from the station on the ground is proposed, the authors study the placement of a single UAV-mounted base station. An algorithm with successive placement along a spiral path towards the center is presented [3]. In [4,5], the positioning of UAVs as relays is discussed, but the placement of UAV is on a line which is not in accordance with practical coverage. The Interference of UAV-mounted base station with underlaid D2D network is further investigated in [6]. However, some of the works don't cover all the users to be served on the ground, some of the work consists of only one UAV-mounted base station, there are not multi-UAVs to cooperate to cover the users. Besides, the works doesn't determine the height of UAV-mounted base station. Since the character of the air-to-ground channel is different from the terrestrial channel, solve the problem of placement of UAV must take the height parameter into consideration.

After the placement of UAV-mounted base stations is determined, we should consider the spectrum allocation of UAV-mounted base stations. The frequency resource is limited, in order to satisfy data rate demand, it should adopt frequency reuse scheme in each cell. This will cause inter-cell interference of the UAV cells. Especially the UAV is deployed according to the nodes on the ground, if the distribution of the nodes is inhomogenous, the coverage of adjacent UAV-mounted base station may overlap, it makes the interference more severe. Soft frequency reuse (SFR) is a widely used scheme to deal with inter-cell interference in conventional terrestrial cells. In this paper, we design a similar scheme to allocate the frequency resource.

SFR is a spectrum reuse method which is used for improving spectrum efficiency and reduce interference in LTE networks in [7]. The frequency is divided into groups for center region and edge region. Meanwhile, power control is used with SFR. The authors in [8] divide the bandwidth into two segments, allocating them to center region and edge region respectively with different power level. In [9], a multi-level SFR is proposed, the spectrum is divided into three segment and the adjacent cells rotate the use of these segment to reduce interference.

To the best of our knowledge, the works presented have not considered UAV cells frequency reuse. In this paper, we first place the UAV-mounted base stations according to the distribution of nodes on ground to cover all nodes. Then we choose an optimal height of each UAV-mounted base station due to the implicit relation of coverage radius and height which can be seen from the air-to-ground channel. Sine the 3-D placement of UAV is solved, we determine the spectrum allocation and power control of UAV stations with interference limitation among neighboring cells. Diverging from with resource scheduling beforehand, the algorithm we proposed is dynamically allocating spectrum and adjust according to network traffic distribution.

The rest of the paper is organized as follows. In Sect. 2, we describe the system model and discuss the air-to-ground channel in detail. Then we present the two main problems, the placement of UAV-mounted base station and the frequency reuse pattern. Next, in Sect. 3, the algorithm of the solution to the problem mentioned above is proposed. In Sect. 4, numerical simulations to validate our algorithms is presented. Finally, Sect. 5 concludes this paper.

2 System Model

UAV-mounted mobile base station is used to provide coverage for users in terrestrial network without fixed infrastructure, achieve the connectivity of the network in disasters and relay for the nodes in remote area. UAV-mounted base station differs from other base stations. In contrary of the macro cell base stations that used in cellular networks, the base stations on UAV platform can adjust its position according to the distribution of users on the horizontal plane. Besides, UAV platform differs from other High Altitude Platforms reaching the upper layers of the stratosphere, UAV platforms are more easily to employ.

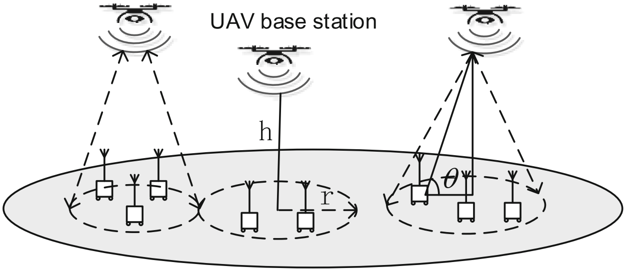

Fig. 1. A wireless network with UAV-mounted base stations

2.1 Channel Model

We consider a wireless network with K users on the ground, denoted by $\mathcal{K} = \{1, 2, \cdots K\}$. Assuming that the location information of these nodes is known by UAV-mounted base stations. Each of the known locations is given by two-dimensional coordinates (x_i, y_i). The characteristic of UAV-mounted base station is utilizing air-to-ground link. Air-to-ground channel distinguishes from the terrestrial channel such as Rayleigh channel or Rice channel. Although different literature use these channels to study air-to-ground channel widely, it is not in accordance with practical propagation. This is due to the high probability of Line-of-Sight (LoS) propagation in the air-to-ground channel. Some works on characterizing the air-to-ground channel are available. One of the most complete models is derived in [10] with the help of the channel proposed by ITU [11], which is based on classifying the signal arriving at the receivers into two propagation groups statistically. We adopt this channel in this paper.

The occurrence of two dominant propagation groups LoS group and NLoS group correspond to the LoS condition. The probability of having LoS users depend on the elevation angle θ, as Fig. 1 shows. For the i^{th} user on the ground located at (x_i, y_i), the horizontal distance r_i between a UAV at (x_U, y_U) is $\sqrt{(x_i - x_U)^2 + (y_i - y_U)^2}$. For a UAV at the altitude h, the angle between user i with it is calculated as $\theta = \arctan(h/r_i)$. According to [10], the LoS probability is given by

$$\mathrm{P}_{LoS} = \frac{1}{1 + a \exp\left(-b[\theta - a]\right)}, \tag{1}$$

where a and b are constant parameters depends on the environment such as suburban, urban, etc. the probability of NLoS is $\mathrm{P}_{NLoS} = 1 - \mathrm{P}_{LoS}$.

Assuming the transmitter and receiver antennas is isotropic, the expectation of path loss between a UAV-mounted base station and a terrestrial user is denoted as PL, $PL = \mathrm{P}_{LoS} \times \mathrm{PL}_{LoS} + \mathrm{P}_{NLoS} \times \mathrm{PL}_{NLoS}$, where PL_{LoS} and PL_{NLoS} representing the path loss of different signal groups in air-to-ground link. According to [10], PL measured in db is

$$PL = \frac{A}{1 + a\exp(-b[\theta - a])} + 10\log(h^2 + r^2) + B, \tag{2}$$

where $A = \eta_{LoS} - \eta_{NLoS}$, η_{LoS} and η_{NLoS} are the losses corresponding to the LoS and NLoS groups in db, $B = 20\log f + 20\log(4\pi/c) + \eta_{NLoS}$, f is the carrier frequency.

2.2 UAV-Mounted Base Station Placement

We aim to deploy UAV-mounted base stations so that a terrestrial user is covered by at least one UAV station. Denote the set of UAV-mounted base stations by $\mathcal{M} = \{1, 2, \cdots M\}$. The placement of UAV-mounted base stations is a comprehensive problem which is different from the cell base station on the ground. This is because that determine the location of the UAV-mounted base station is actually choosing the projection coordinates on the horizontal plane (x_j, y_j), $j \in \mathcal{M}$, and altitude of UAV h_j in addition.

The position information of users to be served by a UAV-mounted base station is known, so the area to be covered is determined. However, the coverage area of a UAV is unknown in advance, this is because that UAV-mounted base station coverage radius depends on the height of a UAV, which is to be determined. Due to the characteristic of air-to-ground, the coverage radius of a UAV-mounted base station is not a monotonic function of its height, which can be seen from the path loss expression (2).

Unlike terrestrial cells such as macro or micro cells which are fixed, UAV-mounted base station adjusts the position to serve users on the ground in accordance with the distribution of users changing. So the position of UAV-mounted base station that can bring the network maximum coverage is to be found to accommodate the mobility of user on the ground.

Besides, the bandwidth of a UAV is limited, which means the data rate of a UAV is limited. A UAV-mounted base station can only serve some users on the ground with limited resources. We assume that the total available bandwidth of a

UAV is divided into L different links, which means it can serve L terrestrial users at the same time. In order to cover all the users on the ground, it needs multi-UAVs to cooperate to provide coverage for the area. So the amount of UAV-mounted base stations and the placement of the UAVs need to be determined jointly.

2.3 Frequency Reuse Pattern Allocation

We consider downlink transmission in UAV aided networks since downlink traffic load is larger than uplink. We assume UAV-mounted base station adopts Frequency Division Duplexing (FDD), and the total bandwidth is divided into four segments (i.e., F_1, F_2, F_3, F_4) which are to be assigned to different part of the area as Fig. 2 shows. The distribution of nodes in horizontal plane is not homogenous, some areas where users have heavy traffic to transmit forming hot-spot areas. UAV-mounted base stations to serve users on the ground are more dense in these areas intuitively and vice versa. Due to the mobility of UAV-mounted base station, the UAV-mounted base stations are distributed in accordance with the distribution of traffic on the ground, the UAVs are evenly distributed, so sometimes the UAV cells overlap in edge. In order to decrease interference of adjacent UAV cells, we adopt SFR scheme to allocate different spectrum in cell edges. According to the four-color problem of graph theory, in order to allocate different spectrum in different UAV cells, we need four frequency segments. We propose a novel soft frequency reuse scheme to allocate the spectrum, which means distributing the spectrum according to 4-color frequency reuse pattern. First, a frequency segment is assigned to the edge of the area covered by a UAV-mounted base station, then we use a SINR-based criterion to allocate the other three segments, more details of the algorithm can be found in Sect. 3.

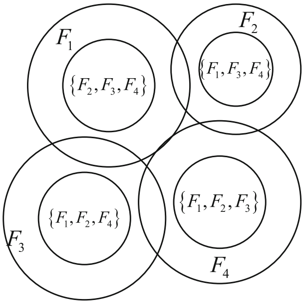

Fig. 2. Frequency reuse examples for 4-color frequency reuse pattern

3 UAV Placement and Resource Allocation Algorithm

In this section, we propose an efficient algorithm to solve UAV-mounted base stations placement problem to provide coverage for all users on the ground in the condition that the users a UAV-mounted base station can serve are limited. Then we propose a practical SFR scheme, to allocate frequency resources for planning UAV cells purpose.

3.1 UAV-Mounted Base Station Placement

The main idea of the UAV-mounted base station placement algorithm is to use divide-and-conquer which is a recursive technique. Due to the resources a UAV-mounted base station has are limited, including spectrum, the storage capacity and the battery, a UAV-mounted base station can only serve a certain number of users on the ground. As noted earlier in this paper, we assume that the spectrum a station holds is divided into L sub-carrier, namely, a UAV-mounted base station can serve at most L users at the same time. The coverage problem is formulated to use M UAV base stations to provide coverage for all the ground users cooperatively.

Since the locations of users on the ground are known to UAV-mounted base stations, first, we place a UAV-mounted base station in the middle of the area to be covered. The UAV-mounted base station detects the amount of the users, if the number of users is larger than L, then we add the number of UAV-mounted base stations to provide service for the target area. We divide the target area into four equal parts. This is because that a square is more accordant with the coverage circle a UAV-mounted base station projection on the ground. A square area is isotropic in four directions and can jointly cover a destination area seamlessly and reduce the occurrence of outlier users to be served.

Then place UAV-mounted base stations in the center of every newly divided square region, UAV-mounted base stations detect whether the nodes in the square area it guarantee to cover is provided coverage. If the amount of the terrestrial users is still larger than a UAV-mounted base station can serve at the same time, L, then repeat the steps above until the number of nodes a UAV serve is small or equal to L. After a UAV-mounted base station is placed, namely a sub-square area is covered by a station, the adjacent UAVs repeat this algorithm to place the next UAV-mounted base station until all users are covered. As a result, the process of determining the placement of UAV-mounted base station uses the recursive technique, which divides the area continuously. We therefore name our proposed algorithm as the divide-and-conquer algorithm, which is summarized in Algorithm 1.

Then the radius of each UAV-mounted base station cell can be calculated. It equals the distance between the projection point of the UAV and the node which is farthest to it. This base station placement method is simple and easy to operate on the UAV platform and saves computational resources for UAV which only has small storage to compute. For our divide-and-conquer algorithm, the complexity is relatively low, reducing energy consumption benefits for UAV platform of limited battery. Besides, this algorithm considers the inhomogenous distribution of the traffic on the ground, it places UAV-mounted base stations according to the distributions of the terrestrial under their conditions where the number of users a UAV-mounted base station can serve is limited. In hot spots,

Algorithm 1. Divide-and-Conquer Placement Algorithm

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Input: terrestrial users location information, $(x_i, y_i)$, $i \in \mathcal{K}$
Output: UAV-mounted base stations set $\mathcal{M}$, with locations $(x_j, y_j)$, $i \in \mathcal{M}$
    Initialization: uncovered terrestrial users location; $\mathcal{M} = \emptyset$, $m = 1$.
while the number of users served by a UAV-mounted base station $> L$ do
    Place a UAV-mounted base station in the center of the area to be covered, and detect the amount of users on the ground.
    If the amount of users to be served is larger than $L$, divide the area into four equals part, repeat step 2.
    Else $\mathcal{M} \leftarrow \mathcal{M} \cup \{m\}$, $m \leftarrow m + 1$.
end while
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the UAV-mounted base stations are more than in the area a relatively small number of users locate in.

3.2 Frequency Reuse Pattern Allocation

In this section, we address the issue of spectrum allocation and power control of UAV-mounted base stations. In order to solve these problems, we fist should determine the height of each UAV-mounted base station. This is because that the coverage radius of a UAV-mounted base station does not only depend on the transmitting power but also the height of a UAV. In the case that coverage radius of a UAV cell is determined, the height has an influence on the transmitting power and the interference of each other.

As described above, the air-to-ground link is different to the terrestrial channel. The power of signal is not a monotone decreasing function of distance but depends on elevation angle θ. To illustrate this, we plot the radius-altitude curve according to expression (2). We assume a path loss threshold, when path loss exceeds this threshold, the user is out of coverage of the UAV-mounted base station. As plots in Fig. 3, as to the same path loss, the UAV-mounted base station at different height corresponds to different coverage radius. An inflection point can be seen on each curve, which means for a given path loss, there is an optimum height can provide a maximum coverage. The optimum height means an optimum elevation angle θ. However, the path loss equation is implicit, there is not an explicit function of the coverage radius R with elevation θ. We find this optimum point by setting the derivative of the radius R with respect to elevation angle θ equals to zero, which yields as follows:

$$\frac{20}{\ln(10)} \tan(\theta_{OPT}) + \frac{abA \exp(-b[\theta_{OPT} - a])}{[aexp(-b[\theta_{OPT} - a]) + 1]^2} = 0. \tag{3}$$

From Eq. (3), we can know that the optimum elevation angle θ only depends on parameters a, b, and A conditioning on environments (i.e. urban, suburban). This also explains the straight line in Fig. 3, in the same environment the optimum θ is at the same value. We use the optimum θ to determine the height of the UAV.

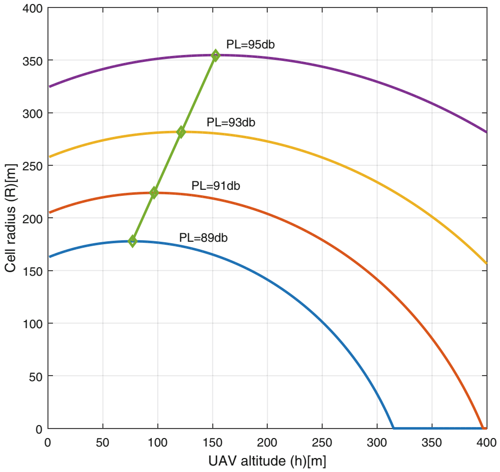

Fig. 3. Cell radius vs. UAV-mounted base station altitude for different pathloss in an urban environment

Since the radius and height of a UAV-mounted base station are determined, the issue of spectrum allocation and power control is to be solved. Here we adopt a soft frequency reuse scheme to allocate spectrum. The coverage area of a UAV-mounted base station is divided into cell edge and cell centers as depicts in Fig. 4 We set a guard band at the cell edge of each UAV. In order to make any two adjacent cells have different spectrum at the edge, the frequency is divided into four segments according to the four-color problem of graph theory. Four spectrum F_1, F_2, F_3, F_4 are available for a UAV-mounted base station.

First, a UAV-mounted base station can sense the guard frequency band which the UAV-mounted base station adjacent to it use. According to the graph coloring problem, the UAV-mounted base station selects a segment different from the segment adjacent cells use, then allocate to its edge region. The other segment is allocated to its center region. We propose an algorithm to design the transmitting power and radius of different frequency segment according to the power of signal and interference.

The useful signal a terrestrial user receives should be larger than a threshold that the signal can be accepted correctly, this yields follows:

$$10\log(P_1) - PL \geq 10log(P_{RXth}), \tag{4}$$

where P_{TX} and P_{RXth} are transmitting power of a UAV-mounted base station and the receiving signal power of a user on the ground. The formulation is evaluated in db. The signal received at the user in edge region is the smallest due to its largest path loss, in order to satisfy the condition in inequation (4), the power of guard segment should be larger than or equal to the P_{TX} derived when using the path loss of the very point at the edge of the UAV-mounted base station coverage area.

For determining the power and radius of other segments, we take two adjacent UAV cells as an example. As shown in Fig. 4, point p_1 and point p_2 are the projection point of UAV-mounted base stations, their coordinates are (x_1, y_1) and (x_2, y_2) respectively, and their guard segment is F_1 and F_2. We assume a point p_3 on the line between p_1 and point p_2, the coordinate of which is $(x_1 + t\,(x_2 - x_1)\,, y_1 + t\,(y_2 - y_1))$, where $t \in (0, 1)$.

In cell 1, segment F_1 is used in edge region, and in cell 2, the same segment is used in center region. The interference caused by adjacent cell should be restricted to guarantee communication quality, we set a SIR threshold of the same spectrum segment. We assume point p_3 is the very furthest node to the UAV-mounted base station in cell 2 using segment F_1, so the distance between p_3 and p_2 is the coverage radius of segment F_1 in cell 2. In order to satisfy the condition above, we have

$$\begin{aligned} &10\log(P_2) - PL_{23} \geq 10log(P_{RXth}), \\ &10\log(P_2) - PL_{23} - (10\log(P_1) - PL_{13}) \geq 10\log(SIR_{th}), \end{aligned} \tag{5}$$

where PL_{ij} representing the path loss between node i, j, and P_i denoting the transmitting power of node i. Substituting the path loss equation, the coordinates of every point, the power and radius of different spectrum segment can be derived.

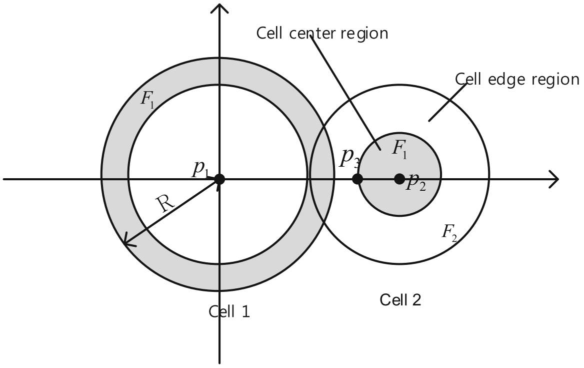

Fig. 4. Single adjacent interfering cell model

4 Numerical Results

Figure 5 illustrates a result of our algorithm in a snapshot, we apply our divide-and-conquer placement algorithm to cover 200 users on the ground. The users are randomly and independently distribute in a square area of 2.6 km^2. The simulation parameter of the air-to-ground channels presented in Table 1 are derived from [2,10]. It is assumed that a UAV-mounted base station can serve at most 40 users at the same time. After dividing the area into small squares, the position

Table 1. Simulation parameters

Description	Parameter	Value
System frequency	f_c	2.5 GHz
Difference of path loss between two propagation groups	A	-20
Parameter for dense urban environment	a	4.88
Parameter for dense urban environment	b	0.43

of a UAV-mounted base station is determined, the radius is then calculated and the optimum height of UAVs is derived by solving the 3-D placement problem using the algorithm proposed above. Note that the UAV cells size is not equivalent, this is due to the distribution of nodes on the ground. Each terrestrial user is supplied coverage by a UAV-mounted base station. Some nodes are on the edge of the UAV cell, and some area isn't covered by a UAV-mounted base station, this means that the transmitting power of UAV is not wasted, and the algorithm is efficient.

Figure 6 shows the frequency allocation using the algorithm we propose. We choose a snapshot of the wireless networks. In this figure, frequency segments are noted next to the edge of circles with different radius, which means within the coverage circle, this segment is available. The coverage radius of different frequency segments are unequal, it depends on the interference of the same segment used in UAV cells surrounding it. We can further see that edge region of the UAV cells is separated by guard segment which decreases the interference from adjacent cells. The other frequency segment is allocated in the center area of the UAV cell to reuse to elevate spectrum efficiency. This algorithm is flexible and simple to operate on UAV platform which is power and capacity constrained.

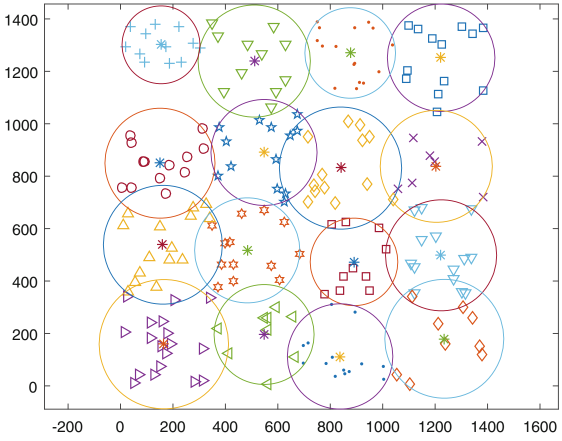

Fig. 5. Placement of UAV-mounted base stations to cover all users on the ground

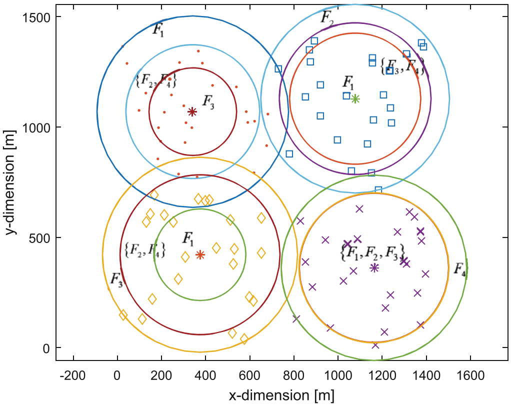

Fig. 6. Frequency allocation scheme in each UAV cells

5 Conclusion

In this paper, we have proposed a novel UAV-mounted base station placement solution for coverage problem, termed as divide-and-conquer algorithm. The proposed algorithm is low-complexity and occupies small storage, it is suitable to operate on UAV which is battery and storage constrained platform. Using this algorithm the UAV-mounted base stations which can serve a fixed number of users at the same time can cooperate to cover all terrestrial users. In addition, we have presented a soft frequency reuse scheme, the allocations of transmit power and spectrum segment are not fixed prior, it is dynamically deployed according to the position and interference of adjacent UAV cells. The algorithm achieves a good performance. We believe that these algorithms can provide guidelines for UAV-mounted base station design.

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