Cell Association in Energy-Constrained Unmanned Aerial Vehicle Communications Under Altitude Consideration

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***Abstract*—In this paper, the total transmit power of Unmanned Aerial Vehicles (UAVs) which are deployed as aerial base stations is minimized by adjusting the altitudes of different UAVs. We assume that the UAVs adopt the frequency division multiple access (FDMA) technique to serve ground users that are distributed in a certain geographical area. For the given two-dimensional locations of UAVs and the distribution of ground users, we find the optimal altitude of each UAV so that it covers all the ground users nearby and provides services with the minimum transmit power. Our formulated problem is separated into two sub-problems: (1) cell association and (2) transmit power minimization. We find the optimal altitude of each UAV in the first sub-problem by using K Means clustering algorithm. In the second sub-problem, we minimize the transmit power of UAV by using the solution of the previous sub-problem. Exploiting convex optimization, we jointly find the optimal altitude and the optimal transmit power of each UAV under its QoS constraints. In essence, the resulting optimal altitudes can lead to lower transmit power of the UAVs in the network compared to the cases when UAVs are deployed at a fixed altitude.**

***Index Terms*—UAV, Cell Association, K Means Clustering, Convex Optimization**

I. Introduction

Unmanned Aerial Vehicles (UAVs), such as drones and balloons, have been used in various applications, for instance, surveillance and monitoring, military, telecommunications, delivery of medical supplies and rescue operations. However, some issues of navigation, control, and autonomy have been focused by conventional UAV-centric research, since the applications were typically robotics or military oriented [1]. Due to the advancement of UAV technology, deploying UAVs as flying base stations becomes a promising solution to extend the wireless coverage and enhance the performance such as capacity, quality of service (QoS) and latency. Especially in areas where there is a huge number of ground users and existing terrestrial base stations are partially damaged or cannot be fully operated. Since UAVs can not only move freely, flexibility but also their altitudes can be adjusted, the line-of-sight communication links to the ground users can be established. They can be flexibly deployed in a three-dimensional location and fully controlled by setting proper trajectory design to avoid interference. As UAVs are suitable to serve as airborne communication hubs such as aerial BSs and/or relays, they are especially useful for practical scenarios that require on-demand deployment in temporary events or emergency situations (such as natural disaster) when the ground infrastructures are insufficient or unavailable [2]. UAVs can be categorized into two groups, fixed-wing and rotary-wing, each has its strong and weak points. For instance, although fixed-wing UAVs can fly with high speed and have heavy payload, they cannot hover in the air and have to move forward to remain aloft. In contrast, rotary-wing UAVs have the ability to travel in any direction as well as to stay stationary in the air despite their limited mobility and payload. Thus, the types of UAVs can be different based on the applications.

Generally, high-altitude platforms (HAPs), such as balloons can provide reliable wireless coverage for wide geographical areas as they operate at tens of kilometers above the ground. When compared to HAPs, low-altitude UAVs (drones) operating at an altitude that does not exceed several kilometers have many advantages over HAPs since they can be deployed quickly and efficiently for unforeseen or time-limited missions. Moreover, with the help of low-altitude UAVs, ground users can establish the short-range line-of-sight (LoS) communication links in most scenarios, which can significantly improve the performance of the existing system or HAPs can be used as relays over long-distance LoS links [3] . In addition, using their mobility, communications can be adaptively designed to enhance the performance of the system.

Despite many advantages, UAVs have enormous challenges to be tackled such as air-to-ground channel modeling, trajectory optimization, hover time optimization and energy-efficient deployment. Rather than the deployment problems, the energy utilization of UAVs is also a significant challenge [4]. Further investigations are needed to be considered for many practical scenarios, such as frequency reuse, inter-cell interference and backhaul in cellular system.

II. Recent Work

Authors in [5] shed light on a comprehensive tutorial on potential benefits and applications of UAVs in wireless com-

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munications. They also described fundamental open problems and provided some analytical frameworks, such as, the optimization theory, the stochastic geometry, the optimal transport theory, and so on. Based on the maximum possible hover time of UAVs, the work in [5] investigated the optimal cell partitioning problem to maximize users' data requirement under a fair resource allocation scheme by employing the powerful mathematical framework of optimal transport theory. Then, they minimized the average hover time of UAVs to serve the ground users with the given load requirements. In their proposal, they considered that UAVs stay stationary over a given geographical area to serve the ground users that are distributed according to two-dimensional truncated Gaussian distribution. In [4], the authors contributed the power-efficient deployment of multiple UAVs which act as flying base stations by dividing into two sub-problems. In above two works, the mobility of UAVs was not taken into account. The authors in [6] proposed a statistical propagation model for predicting the air-to-ground path loss between a low altitude platform and a terrestrial terminal. The iterative parameter-assisted block coordinate descent method was proposed in [2] to optimize the UAV trajectory and OFDMA resource allocation.

Authors in [7] presented the efficient joint transmit power and trajectory optimization algorithm by considering a network in which one UAV is deployed under a flight speed constraint. The fixed altitude of UAV was only considered in most of the previous work. In [8], we investigated the total transmit power minimization of static UAV networks based on SNR constraints of ground users. In [9], cache-enabled UAVs were deployed in cloud radio access networks (CRANs) by maximizing the QoE of mobile users with the minimum transmit power of the UAVs. They proposed the conceptor-based echo state network (ESN) approach to predict the behavior of the users. Authors in [10] considered a network in which a single fixed-wing UAV is deployed as a relay to serve two ground terminals. Based on the discretization of the time interval, they maximized the throughput of the system by optimizing the trajectory and the transmit power of the UAV. In this paper, the main contribution is the transmit power minimization and cell association under altitude consideration satisfying the data rate requirements of the users. We exploit K Means clustering algorithm for cell association problem and convex optimization for the transmit power optimization problem.

This paper is organized as follows. The system model is presented in Section III. In Section IV, we formulate the cell association problem and transmit power minimizing problem. In Section V, the simulation results are illustrated using the proposed mechanism as mentioned in section IV. Then, we conclude the paper in Section VI.

III. System Model

For our system model, we consider a two-dimensional geographical area $\mathcal{A}$ in which a set $\mathcal{N} = \{1, 2, \ldots, N\}$ of ground users are uniformly distributed and a set $\mathcal{I} = \{1, 2, \ldots, I\}$ of UAVs are deployed as flying base stations that can provide wireless services to the ground users. Each UAV i will connect and serve all the ground users under its coverage. Note that, the number of cell partitions in that area is the same as the number of UAVs. In our system model, we deploy rotary-wing UAVs since they can stay stationay (hover) and move in the air. Users in each cell partition $\mathcal{D}_i$ will be served by a UAV which adopts FDMA technique to provide wireless services. Furthermore, we consider the downlink scenario and the predefined two-dimensional locations of UAVs. Since the distance between a UAV and a user affects the channel quality, the main contribution is to find the optimal altitude of each UAV at which ground users experience the minimum path loss. On the other hand, it can provide the maximum SNR of ground users with the minimum transmit power. Since there is a tradeoff between the altitude and the path loss, deploying UAVs at the optimal altitudes is of paramount importance.

Let the three-dimensional coordinates of UAV i is $(u_i,\, h_i)$ where $u_i = (x_i,\, y_i)$ and $s_n = (x_n,\, y_n)$ is the coordinates of ground user n. For the given two-dimensional coordinates of UAVs, the ground users are associated to a nearby UAV above them by using K Means clustering algorithm. Since there can be different number of users under the different UAVs' coverage, we need to increase the altitude of UAV under which there are larger number of users in order to provide larger coverage area.

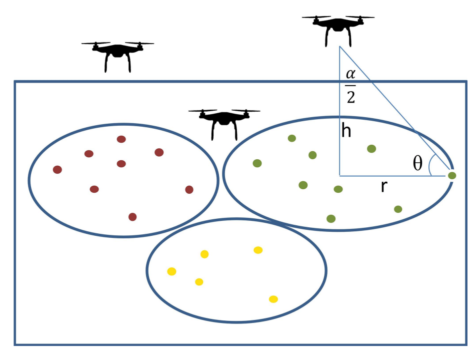

Fig. 1: System Model

IV. Problem Formulation

In our model, we consider the probabilistic path loss model for air to ground channel because of scattering, multi-path components due to reflection, foilage, and so on. The path loss between UAV i and user n at the location $(x,\, y)$ is formulated as given by [6]:

$$\beta_{i,n} = \begin{cases} \left(\frac{4\pi f_c d_0}{c}\right)^2 \left(\frac{d_{i,n}}{d_0}\right)^2 \eta_{LoS} \\ \left(\frac{4\pi f_c d_0}{c}\right)^2 \left(\frac{d_{i,n}}{d_0}\right)^2 \eta_{NLoS} \end{cases} \tag{1}$$

where f_c is denoted as the carrier frequency, c is the speed at which the light travels, η_{LoS} and η_{NLoS} are the attenuation factors for line-of-sight and non-line-of-sight link respectively and d_0 is the free-space reference distance. The distance between UAV i and user n located at (x, y) under its footprint is,

$$d_{i,n} = \sqrt{\left\| u_i - s_n \right\|^2 + h_i^2} \tag{2}$$

We consider d_0 = 1 m and λ = $\left(\frac{4\pi f_c}{c}\right)^2$.

The line of sight probability from UAV i to ground user n as given by [5]:

$$P_{LoS}^i = a\left(\frac{180}{\pi}\theta_{i,n} - 15\right)^b \tag{3}$$

$$P_{NLoS}^i = 1 - P_{LoS}^i \tag{4}$$

where a and b are constant parameters which impact the environmental conditions. θ_i is the angle of elevation between user n and UAV i in radian and it can be calculated by:

$$\theta_{i,n} = \sin^{-1}\left(\frac{h_i}{d_{i,n}}\right) \tag{5}$$

$$r_i = h_i \tan\left(\frac{\alpha}{2}\right) \tag{6}$$

In (5), although the higher altitude of UAV can provide greater LoS probability, it can increase the path loss which results in degrading SNR. Since, altering the height of UAV can also vary the coverage area, we need to find the optimal altitude not to overlap between the coverage regions of UAVs as well as to serve the users with better link quality. It should also be noted that the integrated coverage regions (cell partitions) is the area of interest. α (in degree) is the UAV's directional antenna half beamwidth which is constant. Then, the average path loss between UAV i and ground user n is:

$$\tau_i = \lambda d_{i,n}^2 P_{LoS}^i \eta_{LoS} + \lambda d_{i,n}^2 P_{NLoS}^i \eta_{NLoS} \tag{7}$$

Hence, the received signal power of user n when it is connected to UAV i is:

$$P_{i,n}^r = \frac{p_{i,n}}{\tau_i}, \forall n \in \mathcal{N} \tag{8}$$

where $p_{i,n}$ is the transmit power of UAV i to user n. The signal to noise ratio (SNR) of user n located at (x, y) if it connects to UAV i is given by:

$$SNR_n^i = \frac{P_{i,n}^r}{n_0}, \forall n \in \mathcal{N} \tag{9}$$

where n_0 is the noise power spectral. We consider that all UAVs operate in FDMA technique. Then, the data rate of user n in cell partition $\mathcal{D}_i$ associated by UAV i can be calculated by:

$$R_{i,n} = \frac{B_i}{|\mathcal{D}_i|}\log_2\left(1 + SNR_n^i\right), \forall i \tag{10}$$

where B_i is the bandwidth of UAV i and $|\mathcal{D}_i|$ is the number of ground users in cell partition $\mathcal{D}_i$.

Now, we formulate our optimization problem as follows:

$$\begin{aligned} \min_{h_i, p_{i,n}} \quad & \sum_{i=1}^{I}\sum_{n=1}^{|\mathcal{D}_i|} p_{i,n} \\ \text{s.t} \quad & C_1 : R_{i,n} \geq \epsilon, \forall n \\ & C_2 : \cup_{i \in \mathcal{I}} \mathcal{D}_i = \mathcal{A} \\ & C_3 : \mathcal{D}_x \cap \mathcal{D}_y = \phi, \forall x \neq y \in \mathcal{I} \\ & C_4 : \sum_{n=1}^{|\mathcal{D}_i|} p_{i,n} \leq P_{max}^i, \forall i \end{aligned} \tag{11}$$

where the constraint C_1 captures that each user gets its required data rate. Furthermore, the equality constraints in C_2 and C_3 guarantee that the integration of all cell partitions covers the entire area of interest and there is no overlapping between them. Constraint C_4 ensures that the transmit power of UAV i which serves all the ground users under its coverage area does not exceed its maximum transmit power.

It is difficult to tackle the optimization problem in (12) since there is a mutual dependence between the height and the transmit power. So we divide our problem into two sub-problems: (1) cell association problem and (2) transmit power minimization problem. We determine the optimal altitude of each UAV by using K Means clustering approach to tackle the first sub-problem. For the given heights of all UAVs, since our minimization problem is convex, we solve the latter problem using convex optimization.

A. Cell Association Problem

Here, given the two-dimensional locations of UAVs and the users, the users which are proximal to UAV i are grouped into one cell and served by UAV i. We employ an efficient K Means clustering approach to solve our cell association problem. By assigning users to the nearest UAV, it can reduce path loss as well as transmit with minimum power. Note that the locations of ground users can be collected by a central controller which is installed on the UAVs. Considering the UAV's location as the centre of a cluster, we calculate the minimum coverage radius of UAV i to serve all the ground users within a cluster as follow:

$$r_{min} = \max_{n \in \mathcal{D}_i} \left\| s_n - u_i \right\|, \forall n \in \mathcal{D}_i \tag{12}$$

Then using (6), we calculate the heights of UAVs.

Algorithm 1 Cell Association Algorithm

1: **Input:** u_i = (x_i, y_i), $\forall i$, s_n, $\forall n$
2: **Output:** $\mathcal{D}_i$ = {(x,y)}
3: Generate cell partitions
4: Compute minimum coverage radius r_{min} using (12)
5: Compute h_i using (6)

B. Power Minimization Problem

TABLE I: Simulation Parameters

Parameter	Description	Value
f_c	Carrier Frequency	2 GHz
n_0	Noise Power Spectral	-170 dBm/Hz
η_{LoS}	Attenuation Factor for LoS Link	3 dB
η_{NLoS}	Attenuation Factor for NLoS Link	23 dB
B	Bandwidth of each UAV	10 MHz
ϵ	Data Rate Requirement per User	1 Mbps
N	Total Number of Users	100
a,b	Environmental Factors	0.36, 0.21 [6]

Given the heights of UAVs, we minimize the transmit power of the UAVs satisfying the data rate requirements of the users. Then, the optimization problem is formulated by:

$$\begin{aligned} \min_{p_{i,n}} \quad & \sum_{n=1}^{|\mathcal{D}_i|} p_{i,n} \\ \text{s.t} \quad & C_1 : R_{i,n} \geq \epsilon, \forall n \in \mathcal{D}_i \\ & C_4 : \sum_{n=1}^{|\mathcal{D}_i|} p_{i,n} \leq P^i_{max}, \forall i \end{aligned} \tag{13}$$

V. Simulation Results

For our simulation, we consider a system with 5 UAVs and 100 ground users which are uniformly distributed in the rectangular area of size 500 m × 500 m.

In Fig. 2, the clusters of users associated to the UAVs are illustrated based on the distribution of ground users. As we can see from Fig. 2, there are 5 cell partitions with different sizes and the number of users under the coverage of UAV 1, UAV 2, UAV 3, UAV 4 and UAV 5 are 14, 20, 27, 21 and 18 respectively. According to the size of cell partition, we adjust the altitude of each and every UAV in the system so that it can provide the whole coverage to the users associated to it.

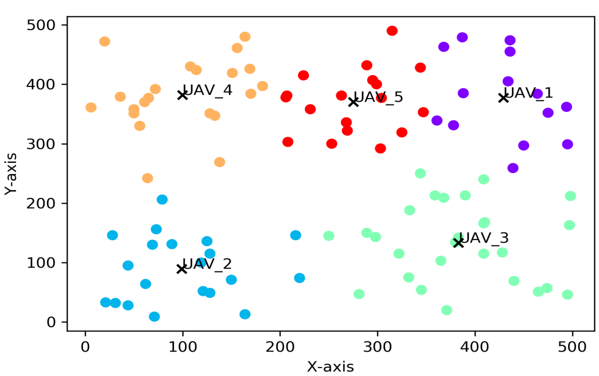

Fig. 2: Cell Association

Fig. 3 shows the total transmit power of each UAV for two scenarios. As we can see from Fig. 3, the proposed scheme outperforms the cases in which UAVs are deployed at a fixed altitude. For our simulation, we set 200 m for the fixed altitude of the UAVs. Obviously, the total transmit power of UAV 3

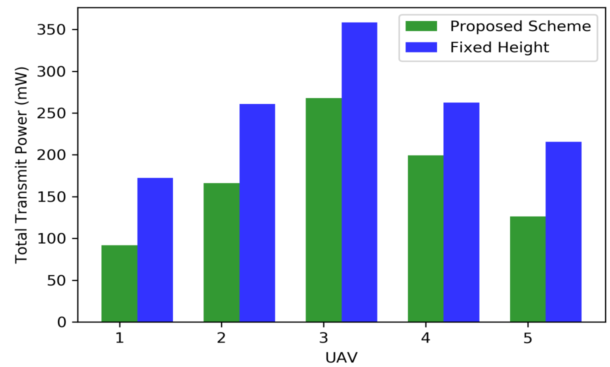

Fig. 3: Total Transmit Power

is higher than any other UAVs since there are the highest number of users under its coverage. UAV 1 needs the smallest transmit power. The reason is that it has the lowest number of users which is 14. According to our simulation results, the total transmit power of UAVs deploying at optimal altitudes is significantly lower than that of UAVs which are at a fixed altitude.

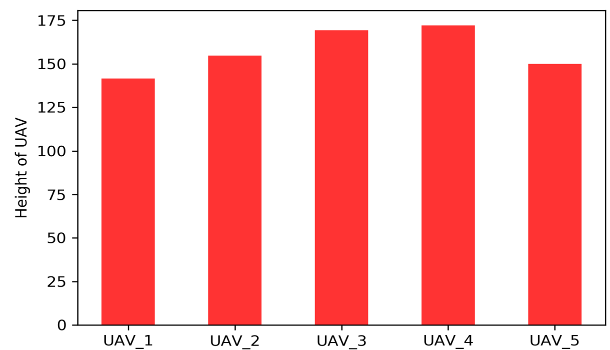

Fig. 4: UAVs' Altitudes

In Fig. 4, the height of UAV 3 is 170 m which is greater than the others except UAV 4 which is at 172 m. This is due to the fact that UAV 4 needs to fly higher to completely cover some users who are at the cell edge and far away from it. The heights of UAV 1, UAV 2 and UAV 5 are 142 m, 155 m and 149 m respectively. For the greater number of users, the UAVs are needed to be deployed at the higher altitude for the wider coverage. In other words, UAV hovers at the low altitude for a small amount of users because flying at high altitude without necessity results in increasing path loss and degrading the system performance.

VI. Conclusion

In this paper, based on the distribution of users, we find the optimal altitudes of UAVs which are deployed as aerial base stations so that the total transmit power of the whole network is minimized. We divide our proposed problem into two sub-problems. In the first sub-problem, we find the optimal altitude of each UAV by using K Means clustering algorithm. In the second sub-problem, we minimize the transmit power of UAVs by using the solution from the previous sub-problem. We jointly find the optimal altitude and the transmit power of each UAV under the QoS constraint. The results have shown that the total transmit power of UAVs in the proposed solution outperforms the scenarios in which UAVs are at the fixed altitude. For our future work, we will investigate the optimal bandwidth allocation of UAVs which serve ground users under the delay constraint.

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