Optimal 3D Trajectory Design for UAV-assisted Cellular Communications in the Post-disaster Scenarios

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Summary

Unmanned aerial vehicle (UAV) assisted wireless communication has been recently proposed as an effective solution to provide wireless connectivity to ground users which can improve the network coverage area and spectral efficiency. In this paper, we consider the post-disaster network scenario where users are isolated from the network infrastructure. We investigate the best positioning of the UAV in terms of the optimal trajectory as well as UAV vertical location to cover as many ground users as possible to improve spectral efficiency. When the trajectory is optimized, the optimal transmit power within the available power budget is then obtained. The simulation results demonstrate that the proposed UAV-enabled wireless communication technique improves the overall spectral and energy efficiency.

KEYWORDS:
UAVs, Poisson cluster process, trajectory optimization, energy efficiency, spectral efficiency.

1 | INTRODUCTION

The demand for wireless applications beyond the fifth generation (B5G) will exponentially increase which introduces new challenges, e.g., the minimum quality-of-service (QoS) irrespective of users' location and time. The challenge that every mobile network operator has to face is to provide the best network quality and ubiquitous coverage when there is a huge gathering of mobile users during, e.g., sports events and concerts. One of the proposed solutions is to fly unmanned aerial vehicles (UAVs) as temporary base stations to route the users' uplink traffic to the nearest base station[1]. Moreover, UAVs deployment would possibly solve many technical issues during the post-disaster network where existing network components are congested or partially dysfunctional. Since UAVs have strong line-of-sight (LoS) communication with the end users, the user throughput and network coverage can be significantly improved.

The full potential of UAV-enabled cellular communication can be exploited only when the horizontal and vertical positions of the UAVs can be optimized in real-time. The major challenge in such a communication system in comparison to the traditional cellular system is the mobility of UAV relays or base stations (BSs) that makes it difficult to measure the channel state information[2]. On the other hand, there is more flexibility in system design due to the fact that there exist multiple tradeoffs among UAV height, antenna beamwidth and transmit power. For example, larger beamwidth covers more ground users and increases the transmit power and interference footprint. For the given beamwidth and transmit power, higher UAV altitude covers more users but the system throughput is significantly decreased due to the higher path loss. Also, a novel 3-D nonstationary geometry-based stochastic model for UAV-to-ground channel estimation is presented in[3]. Many techniques have been proposed recently to achieve efficient UAV-enabled cellular communication. The minimum number of aerial BSs and their placement to provide coverage to users with minimum QoS is studied in[4]. The UAV-supported clustered NOMA for the Internet of Things is proposed in[5] where UAV height and trajectory are optimized to get maximum throughput on the clustered user terminals. A

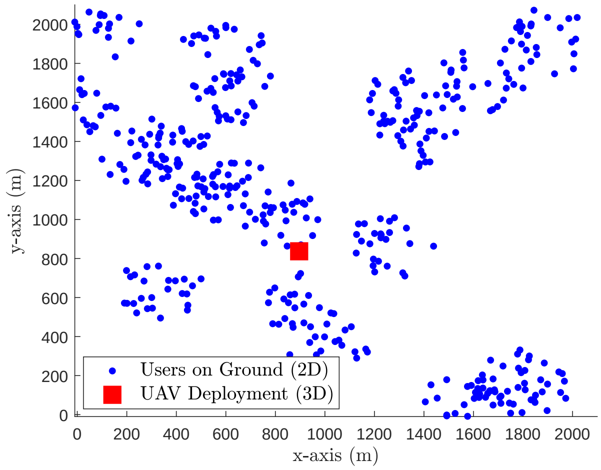

Figure 1 The user distribution following Poisson cluster process in 2D plane and initial deployment of UAV above users.

different perspective of UAVs has been studied in[6] where UAVs are used for wireless power transfer to the ground terminals, which is important for Internet-of-Things (IoT) applications.

The tradeoff between UAV flight time and energy consumption has been reassessed by different settings of clustering radius and the maximum flight speed[7]. Therefore, the flight time and maximum flight speed are related and constrained by each other, there may be multiple combinations of mission time and maximum flight speed which makes this a multi-objective optimisation problem[8]. Furthermore, the UAV trajectory design for dynamic environments where users constantly move and thus change the node distribution is a more challenging task[9]. Such challenges motivate us to simplify the complex UAV trajectory optimisation problem into a simplified single UAV trajectory design problem in this paper. This can be extended further to analyse the multiple UAV dynamic network environment. In this paper, we investigate the best positioning of UAVs and optimal transmit power control during the typical post-disaster network scenario. The best UAV position is obtained by optimizing the horizontal trajectory and vertical position to maximize the performance of the network in terms of coverage, throughput and energy efficiency. It is assumed that the UAVs are equipped with a directional antenna and the beamwidth is adjusted at a fixed angle and does not change. The user distribution is considered to be a Poisson cluster process (PCP) which resembles the user distribution during post-disaster scenarios, e.g., earthquakes or flooding, where users are dispersed as a cluster and the set of clusters are distributed as per the Poisson point process.

2 | SYSTEM MODEL

We consider the UAV-enabled wireless communication network as shown in Fig. 1, where one UAV is deployed to serve the ground user terminals. The post-disaster network scenario is considered where the users are either partially or fully isolated from the cellular network. The UAV is deployed at altitude h_u, where $h_{min} \leq h_u \leq h_{max}$, and the minimum and maximum altitude, i.e., h_{min} and h_{max}, of UAV is decided by the aviation authority. The position of the horizontal axis is (x_u, y_u), where $x_{min} \leq x_u \leq x_{max}$, $y_{min} \leq y_u \leq y_{max}$, depends on the network deployment area and the user distribution. The number of users communicating with the UAV and their positions are always known in the considered system model.

A UAV is deployed above the disaster area which serves $k = \{1, \dots, K\}$ ground terminals. The initial location of the UAV in 3D space is randomly chosen at $\{x_u, y_u, h_u\} = \{x_0, y_0, h_0\}$. The hovering time of UAV is T which is divided into $n = \{1, \dots, N\}$ time slots of duration t, i.e., $T = \sum_{n=1}^{N} = Nt$. The UAV stays at a particular 3D location for a duration of t. Therefore, the random spatial location of UAV is denoted by $\{x_u(n), y_u(n), h_u(n)\}$ at n^{th} time slot. The choice of N incorporates the tradeoff between the accuracy of optimal trajectory and transmit power to the complexity of the algorithm. Another important parameter is the transmit power of UAV, i.e., $P_t \leq P_{max}$, which must be optimized for better system performance.

The air-to-ground path loss model significantly depends on the probability of LoS in the considered UAV-enabled communication systems, which is calculated as $\Pr(\text{LoS}) = \frac{1}{1+a\exp(-b(\frac{180}{\pi}\theta - a))}$, where a and b depend on the environment, e.g., rural, urban etc. and $\theta = \tan^{-1}(\frac{h}{r})$ is the elevation angle where h is the altitude of UAV and r is the horizontal distance from the receiver. The mean path loss in the considered scenario according to[10] is as follows.

$$\mathrm{PL(dB)} = 20log\left(\frac{4\pi f_c d}{c}\right) + \mathrm{Pr(LoS)}\eta_{LoS} + \mathrm{Pr(NLoS)}\eta_{NLoS}, \quad (1)$$

where f_c, c and d are the carrier frequency, speed of the electromagnetic wave and distance between UAV and receiver, respectively. Moreover, $\mathrm{Pr(NLoS)} = 1 - \mathrm{Pr(LoS)}$, η_{LoS} and η_{NLoS} are the additional losses to the free space propagation for LoS and NLoS components, respectively which depend on the considered network environment.

The users $k = \{1, \dots, K\}$, at n^{th} time slot, are distributed following the PCP, where k^{th} user location is represented by $\{x_k(n), y_k(n), 0\}$ considering the height of the user is negligible compared to the height of the UAV base station. The PCP Φ_k is defined as $\Phi_k = \bigcup_{\alpha \in \Phi^*_{(x_\alpha, y_\alpha, h_\alpha)}} \alpha + \beta^\alpha_k$, where $\Phi^*_{(x_\alpha, y_\alpha, h_\alpha)}$ is the projection of point process on (x, y)-plane which is the parent Poisson point process of density $\lambda_{(x_\alpha, y_\alpha)}$ and β^α_k is the offspring, i.e., users point process where each point at β^α_k is i.i.d around the $\Phi^*_{(x_\alpha, y_\alpha, h_\alpha)}$ with the user density $\lambda_{(x_\alpha, y_\alpha, 0)}$. Since users are distributed according to PCP, the k^{th} user location at n^{th} time slot is represented by $(x_k(n), (y_k(n), 0)$ considering the height of the user is negligible compared to the height of the UAVs. The downlink channel gain between the UAV and the user $k = \{1, \dots, K\}$ is obtained as follows:

$$g^k_u[n] = \frac{\delta_0}{(x_u[n] - x_k[n])^2 + (y_u[n] - y_k[n])^2 + (h_u[n] - 0)^2}, \quad (2)$$

where δ_0 is the reference channel power gain which depends on the considered path loss model in (1). Only one UAV is deployed to optimize the optimal positions and transmit power. Therefore, subscript u is removed for brevity. Moreover, downlink OFDMA is considered where the total bandwidth B is equally divided among the UAV and user pair. Since this is an isolated network scenario, the co-channel interference is negligible from the existing cellular users. When the transmit power is $P_{t,k}[n]$ for user k and time-slot n, the received signal-to-noise-ratio (SNR) is as follows:

$$\mathrm{SNR}[n] = \frac{P_{t,k}[n]\delta_0}{\left[(x[n] - x_k[n])^2 + (y[n] - y_k[n])^2 + h^2[n]\right]\sigma^2}, \quad (3)$$

where σ^2 is the variance of AWGN.The received spectral efficiency for user k is as follows:

$$R_k[n] = \alpha_k \log_2\left(1 + \frac{P_{t,k}[n]\delta_0}{\sigma^2\alpha_k\left[||\boldsymbol{x}_k||^2 + ||\boldsymbol{y}_k||^2 + h^2\right]}\right), \quad (4)$$

where α_k is the allocated portion of bandwidth B to the user k and $P_{t,k}[n]$ is the UAV's transmit power to the user k at timeslot n. Here, $\boldsymbol{x}_k$ and $\boldsymbol{y}_k$ represent the projected distance in (x, y)-axis from UAV to user $k = \{1, \dots, K\}$.

3 | SUM-THROUGHPUT OPTIMIZATION

Here, the aim is to maximize the spectral efficiency on downlink during the post-disaster, which can be formulated as follows:

$$\max_{x[n],y[n],h[n],P_{t,k}[n]} \sum_{k=1}^{K} \alpha_k \log_2\left(1 + \frac{P_{t,k}[n]\delta_0}{\sigma^2\alpha_k\left[||\boldsymbol{x}_k||^2 + ||\boldsymbol{y}_k||^2 + h^2\right]}\right) \quad (5a)$$

$$\text{s.t.} \sum_{k=1}^{K} P_{t,k}[n] \leq \mathrm{P}_{max}, \forall k, n, \quad (5b)$$

$$P_{t,k}[n] \geq 0, \forall k, n, \quad (5c)$$

$$x_{min} \leq x[n] < x_{max}, y_{min} \leq y[n] < y_{max}, \quad (5d)$$

$$h_{min} \leq h[n] < h_{max}, \forall n, \quad (5e)$$

$$\alpha_k \geq 0, \forall k, \sum_{k=1}^{K} \alpha_k = 1. \quad (5f)$$

The constraints (5b) and (5c) are related to the power budget of the UAV, constraints (5d) and (5e) are the location constraints in horizontal and vertical axes, respectively, and constraints (5f) and (**??**) are related to the bandwidth allocation strategy. Here, the optimization parameters, i.e., the 3D trajectory and transmit power, are directly coupled, which makes this problem a non-convex optimization problem. It is therefore intractable to find optimal trajectory in 3D space and transmit power using the standard convex optimization theory. We hereby assume that the user distribution is not significantly changed for a few time slots during the considered post-disaster network scenario. Therefore, we follow the step-by-step approach to solve the optimization problem. When the UAV is deployed during post-disaster, e.g., earthquake or flooding, it is difficult to estimate the user distribution and correct user density in real-time. Therefore, the UAV initial position axes, i.e., $(x[m], y[m], h[m])$, are randomly selected within the minimum and maximum values in the x-axis and y-axis, which depend on the location and area affected by the disaster. The maximum UAV flying altitude is fixed and monitored by aviation authorities, for instance, h_{max} is 250 m in the UK. Moreover, UAV deployment is also a step-by-step approach where height, trajectory and the transmit power are selected at a particular point and assessed at every time slot to readjust these parameters depending on the unpredictable user movements during the post-disaster.

The objectives in this paper are achieved by solving the optimization problem following the real UAV deployment scenario. At particular time-slot n, the first step is to deploy the UAV in a random $(x[n], y[n])$ location within the range. The UAV is kept at height $h[n]$, subchannels are equally distributed, i.e., $\alpha_k = \frac{1}{K}, \forall k$ and the transmit power is fixed at $P_{t,k}[n], \forall k$. Then the optimization problem is as follows:

$$\max_{x[n],y[n]} \sum_{k=1}^{K} \alpha_k \log_2 \left(1 + \frac{P_{t,k}[n]\delta_0}{\sigma^2 \alpha_k \left[||\boldsymbol{x}_k||^2 + ||\boldsymbol{y}_k||^2 + h^2 \right]} \right) \tag{6a}$$

$$\text{s.t. } x_{min} \leq x[n] < x_{max}, y_{min} \leq y[n] < y_{max}. \tag{6b}$$

The UAV then estimates the average downlink throughput and stores it with associated location $(x[n], y[n])$. The users' distribution is estimated based on the arrival control signal from the ground users and changes its position by (δ_x, δ_y) in four directions. The number of times the UAV adjusts its position can be fixed depending on the size of the disaster area and the energy availability of the UAV. At a fixed UAV height, the highest downlink spectral efficiency provides the optimal horizontal position, i.e., $(x^*[n], y^*[n])$ of the UAV. The next step is to keep the UAV within a small circular radius of δ_r about point $(x^*[n], y^*[n])$. The optimal height is then estimated which provides the best coverage, lower path loss and improved throughput. The new optimization is then obtained as follows:

$$\max_{h[n]} \sum_{k=1}^{K} \alpha_k \log_2 \left(1 + \frac{P_{t,k}[n]\delta_0}{\sigma^2 \alpha_k \left[||\boldsymbol{x}_k^*||^2 + ||\boldsymbol{y}_k^*||^2 + h^2 \right]} \right) \tag{7a}$$

$$\text{s.t. } h_{min} \leq h[n] < h_{max}. \tag{7b}$$

The step size of the increment of height, i.e., δ_h, depends on the terrain conditions of the disaster area. This provides the optimal height $h^*[n]$ of the UAV in which the total spectral efficiency is maximized. when the trajectory optimization problem is solved, the final objective is to optimally select the UAV's transmit power for each user within the power budget. The 3D trajectory and transmit powers are now decoupled which makes the optimization problem a convex optimization problem, as shown below, which can be solved by using the standard convex optimization methods.

$$\max_{P_{t,k}[n]} \sum_{k=1}^{K} \alpha_k \log_2 \left(1 + \frac{P_{t,k}[n]\delta_0}{\sigma^2 \alpha_k \left[||\boldsymbol{x}_k^*||^2 + ||\boldsymbol{y}_k^*||^2 + h^{*2} \right]} \right) \tag{8a}$$

$$\text{s.t. } \sum_{k=1}^{K} P_{t,k}[n] \leq \mathrm{P}_{max}, \forall k, n, \tag{8b}$$

$$P_{t,k}[n] \geq 0, \forall k, n, \tag{8c}$$

$$\alpha_k \geq 0, \forall k, \sum_{k=1}^{K} \alpha_k = 1 \tag{8d}$$

4 | SIMULATION AND ANALYSIS

The proposed 3D trajectory and transmit power optimization technique has been summarized in the Algorithm 1. The post-disaster communication network is considered in an urban environment as shown in Fig. 1, where the users are distributed according to the *Poisson point process* inside the cluster and the distribution of clusters follows the Poisson process. The user density of 25 per cluster and 10 clusters have been considered with a radius of 180 m. The maximum transmit power, $P_{t,max}$, in

Algorithm 1 Optimization of 3D trajectory and the downlink transmit power from UAV to the users

Input: Minimum and maximum UAV heights: (h_{min}, h_{max}), Trajectory boundaries: (x_{min}, x_{max}), (y_{min}, y_{max}), Power budget: P_{max}, Initial position:, (x_0, y_0, h_0), Number of user: K.
Output: Optimal 3D Trajectory: ($x^*[n], y^*[n], h^*[n]$), Optimal transmit power: $P^*_{t,k} \forall k$.
Start

1: Set UAV height randomly between h_{min} and h_{max}
2: Adjust ($x[n], y[n]$) to cover large set of $i = \{1, \dots, N\}$ users and calculate $R = \sum_k \log_2(1 + \text{SNR}(k))$
3: When $R = R_{max}$, fix UAV on ($x^*[n], y^*[n]$) and increase UAV height until $h = h_{max}$
4: Optimize height $h^*[n]$ where $\sum_k \log_2(1 + \text{SNR}(k))$ is maximum
5: For the optimal trajectory, numerically solve the optimization problem (8a)-(**??**).
6: Measure and compare the spectral efficiency.

End

UAV is set to 30 dBm whereas the number of subchannels $N = 32$ each with bandwidth 125 KHz and the carrier frequency is set to be 1800 MHz. Thermal Noise Density is considered to be -174 dBm/Hz and other simulation parameters are $\{a, b\} = \{9.61, 0.16\}$, $\{h_{min}, h_{max}\} = \{20 \text{ m}, 350 \text{ m}\}$, $\{\eta_{LoS}, \eta_{NLoS}\}$=$\{1, 20.0\}$ and $\beta_0 = -50$ dB.

At first, the UAV is randomly deployed within the considered area. It starts finding the best trajectory where it can achieve the highest spectral efficiency. At this optimal coordinate, the best UAV height is obtained which provides the maximum network coverage. At this point, the transmit power is selected to maintain the minimum level of performance on the downlink communication. Here, we consider the users get equal bandwidth in each subchannel irrespective of their locations. Moreover, the partial channel state information is also available to the UAV from the users from which the user distribution pattern is known which helps to select the next optimal trajectory point.

The average spectral efficiency, measured in bps/Hz, for a range of transmit power, is shown in Fig. 2a. The proposed optimal UAV positioning always outperforms the case when the UAV's trajectory is randomly chosen. This is due to the fact that the UAV always selects the horizontal and vertical positions according to the mobility and distribution of the ground users and serves comparatively more ground terminals. Moreover, even when the lower transmit power is set, i.e., 1 dBm to 15 dBm, the spectral efficiency of the proposed method is approximately four times more than the random UAV deployment scenario. For instance, at P_t =10 dBm, the proposed optimal trajectory achieves 2.5 bps/Hz spectral efficiency whereas it is just 0.5 bps/Hz for a random deployment scenario. It indicates that the proposed optimal trajectory design is exceptionally energy efficient.

The average spectral efficiency performance when varying the vertical height of the UAV at $P_T = 20$ dBm is shown in Fig. 2b. Here, the spectral efficiency is first increased up to the optimal UAV height in both the proposed and random UAV deployment methods. When the UAV further flies up, the spectral efficiency starts degrading due to the severe signal path loss. However, the proposed optimal trajectory and transmit power technique outperforms the random UAV trajectory irrespective of the UAV altitude. On further observation in Fig. 2b, the optimal UAV height in the proposed method is approximately 50 m where spectral efficiency is 4.7 bps/Hz. On the other hand, the optimal UAV altitude in the random UAV deployment is approximately 100 m where spectral efficiency is 3.11 bps/Hz. Therefore, we can conclude that more users are covered at the lower UAV altitude when the transmit power and UAV 3D trajectory are calculated optimally. As a result, the proposed method needs lower transmit power for a similar performance, which makes it a highly energy and spectral-efficient technique.

5 | CONCLUSION

The UAV-enabled aerial communication network has been considered as an effective solution to provide wireless connectivity to ground users. We investigated the optimal trajectory design for the UAV at optimal altitudes to provide wireless services to isolated users. The simulation results have shown that increasing transmit power from 15 dbm to 25 dbm does not improve spectral efficiency without proper UAV trajectory design. It can also be concluded that the proposed UAV trajectory design technique could improve spectral efficiency by 1.5 bps/Hz at the optimal UAV location and improve network coverage simultaneously. As a future work, the optimal trajectory design in a multi-UAVs scenario to improve both spectral and energy efficiencies will be further investigated.

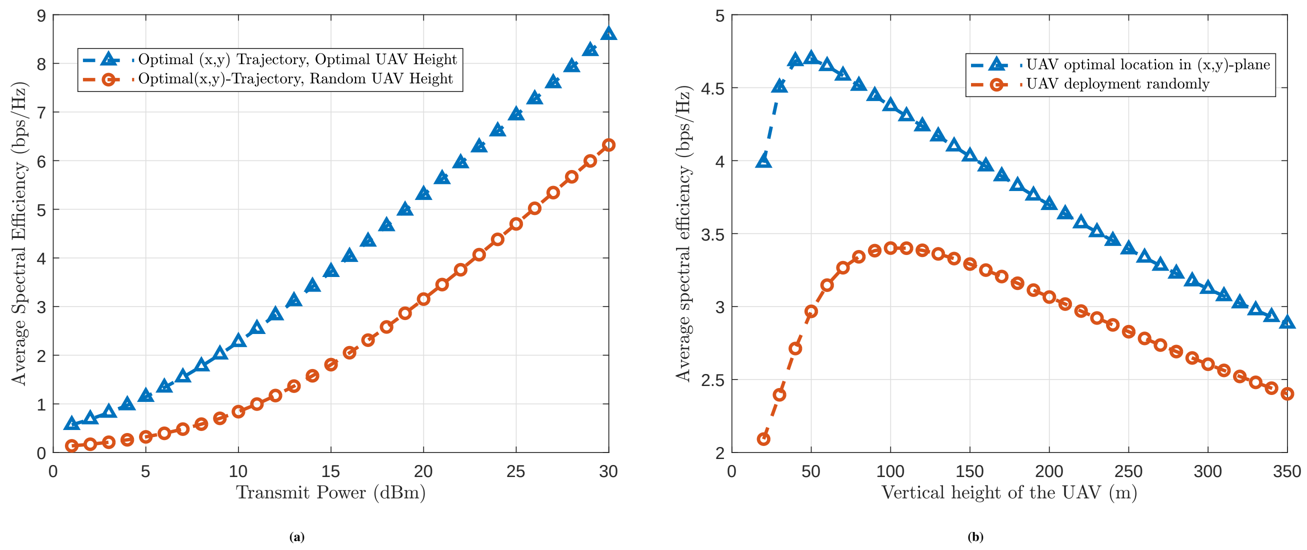

Figure 2 (a) The performance analysis of the proposed method in terms of spectral efficiency *vs.* the transmit power in comparison to the random UAVs (b) The performance analysis of the proposed method in terms of spectral efficiency *vs.* the UAV height in comparison to the random trajectory design.

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