RADIO-MAP-BASED UAV PLACEMENT DESIGN FOR UAV-ASSISTED RELAYING NETWORKS

(Invited Paper)

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ABSTRACT

This paper studies a network with multiple unmanned aerial vehicle (UAV) relays assisting the wireless communication between a base station (BS) and ground users (GUs). All the UAV relays hover at a fixed altitude and each provides connections to a group of GUs. For the first time, the radio-map-based design is considered in UAV-assisted relaying networks, where the radio maps are based on the geographic layout in reality and presenting the realistic channel pathloss. By jointly designing the UAV placement and user assignment, we aim at maximizing the minimum throughput among all GUs in the network. As the radio maps rely on the real layout in the environment, the pathloss is neither convex nor continuous in the location (coordinates), which makes the related designs be highly difficult to analyze. Thus, we propose a particle swarm optimization (PSO)-based design for the problem. We first derive the optimal user assignment scheme and then derive an equivalent reformulation of the problem. Finally, the UAV placement is optimized by deploying PSO technologies, providing an efficient system performance. Via simulation, the performance advantages of the proposed design are confirmed.

Index Terms— radio map, UAV placement design, relaying networks, user assignment, particle swarm optimization (PSO).

1. INTRODUCTION

In recent years, due to the high mobility in the three-dimensional (3D) space and high controllability, unmanned aerial vehicles (UAVs) have shown tremendous potentials in various applications, such as aerial photography, aerial monitoring, geological examination, aerial delivery, and wireless platforms [1]. While being integrated into wireless communication networks, UAVs are confirmed to be capable of providing a higher probability of line-of-sight (LoS) in the aerial-to-ground links than typical ground-to-ground links [2]. To exhaust the promising benefits of UAVs and exploit the additionally introduced degree of freedom [3], UAVs' placement and trajectory design are widely studied. In particular, when UAV is implemented as flying base stations (BSs) with a fixed location, the optimal UAV location deployment has been addressed in [4–6] to enlarge the coverage to ground users (GUs). On the other hand, to utilize the UAV mobility, the authors let UAV fly over the served GUs and improve the throughput [7, 8] and energy efficiency [9, 10] by designing efficient UAV trajectories. Combining with energy harvesting technologies, the designs of UAV trajectories have also shown a significant performance enhancement in UAV-enabled wireless power transfer network [11–13].

Moreover, relaying is well known as an effective approach in compensating the large fading in wireless channels and promoting the capacity and quality-of-service (QoS) [14–16]. By enabling a UAV as a relay, a high flexibility is expected in the system designs. By optimizing the fixed position for a UAV relay, the reliability [17] and capacity [18] of the GUs transmissions can be significantly improved. The trajectory design of a mobile UAV relay is investigated for enhancing throughput [19, 20] and reducing power consumption [21].

All the above works about UAV relays have assumed either an ideal pathloss model [18–21] or a statistical LoS probability model [17]. However, the ideal pathloss model is obviously insufficient for a channel evaluation when the blockage of buildings exists in radio transport, and a statistical LoS probability model only ensures an average performance, while each scenario in practice has its unique topology and unique pathloss values over the topology [22]. To obtain a realistic design, numerous approaches have suggested to rely on the radio map [23, 24], which can precisely present the channel qualities between the transmitter and receiver at any location in the network. Nevertheless, based on the knowledge of radio maps, the fixed (hovering) position of a UAV is optimized in [25] for wireless power transfer networks, and the trajectory of a mobile BS UAV is studied in [26]. So far, to the best of our knowledge, for a cellular network with a BS and multiple UAV relays, it is still an open problem to have the radio-map-based location designs for such multiple UAV relays. In this paper, we address this multi-user multi-UAV-relay scenario and aim at maximizing the minimum throughput among a set of GUs by optimizing the UAV placement and user assignment.

The rest of this paper is organized as follows: In Section 2, we present the system model of our relaying network. Then, the minimal throughout maximization problem is formulated in Section 3. We reformulate the problem based on an optimal user assignment and propose a particle swarm optimization (PSO)-based algorithm in Section 4. Finally, our proposed algorithm is validated through simulations in Section 5 and concluded in Section 6.

2. SYSTEM DESCRIPTION

We consider a cellular network with a single BS, a set of M UAV relays and K GUs being distributed in a rectangular area $[-D_x, D_x] \times [-D_y, D_y]$. An example of the network is shown in Fig. 1. The BS is placed at height $h_0 > 0$ with a fixed horizontal position

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Fig. 1. A network example based on a real building topology in RWTH Aachen University. (Map picture from https://www.google.com/maps/)

(x_0, y_0). We denote by $(w_{x,k}, w_{y,k})$ the position of GU $k \in \mathcal{K} \triangleq \{1, 2, ..., K\}$. M UAVs are deployed as relays and hover at a height of $H > 0$ for data relaying between BS and GUs. We denote the horizontal positions of these UAVs by (x_m, y_m), $m \in \mathcal{M} \triangleq \{1, 2, ..., M\}$. Hence, the set of UAV positions is represented by $(\mathbf{x}, \mathbf{y}) = \{(x_1, y_1), ..., (x_M, y_M)\}$. Then, the distance between the BS and UAV $m \in \mathcal{M}$ is given by

$$d_{0,m} = \sqrt{(x_0 - x_m)^2 + (y_0 - y_m)^2 + (h_0 - H)^2}, \qquad (1)$$

while the distance between UAV $m \in \mathcal{M}$ and GU $k \in \mathcal{K}$ can be expressed as

$$d_{k,m} = \sqrt{(w_{x,k} - x_m)^2 + (w_{y,k} - y_m)^2 + H^2}. \qquad (2)$$

Without loss of generality, we consider a downlink communication from the BS to the GUs with the help of these UAV relays. We denote by P_1 and P_2 the transmit power from BS and from UAVs, respectively. Each GU k is assigned to a UAV relay $a(k) \in \mathcal{M}$. A two-hop relaying protocol is deployed, where each packet is transmitted via two hops, i.e., the BS-UAV hop and the UAV-GU hop. There are no information exchanges between the UAV relays. Note that multiple GUs can be assigned to the same UAV-relay, i.e., there may exist $k_1, k_2 \in \mathcal{K}$, $k_1 \neq k_2$, so that $a(k_1) = a(k_2)$.

Notice that in practice, as implied in Fig. 1, due to the existence of obstacles such as buildings and trees, the pathloss factor of the channel from a GU to a UAV is highly dependent on their positions. Therefore, for each GU k, we apply a radio map $n_k(x_m, y_m)$ for an accurate representation to the channel from UAV m to GU k. In particular, the gain of the channel is modeled as

$$h_{k,m} = \beta_0 d_{k,m}^{-n_k(x_m, y_m)}, \qquad (3)$$

where β_0 denotes the power gain at a reference distance 1m and $n_k(x_m, y_m)$ is the corresponding pathloss factor when UAV m is hovering at position (x_m, y_m). Similarly, the channel gain from the BS to UAV m can be formed by

$$h_{0,m} = \beta_0 d_{0,m}^{-n_0(x_m, y_m)}, \qquad (4)$$

where $n_0(x_m, y_m)$ is the corresponding pathloss factor in the radio map. Denoting the noise power level by σ, the throughput $R_{0,m}$ of the BS-UAV hop and the throughput $R_{k,m}$ of the UAV-GU hop can be formulated as

$$R_{0,m} = \log_2(1 + \frac{P_1 h_{0,m}}{\sigma}), \qquad (5)$$

$$R_{k,m} = \log_2(1 + \frac{P_2 h_{k,m}}{\sigma}). \qquad (6)$$

Note that the information of the radio map is already involved in the above model, following which we can propose a more realistic design based on a specific geographic scenario in reality.

3. PROBLEM STATEMENT

We are interested in a fair design for GUs aiming at maximizing the minimal throughput among GUs. For a data packet with size of S bits, which is supposed to be transmitted from the BS to GU k through UAV relay $a(k)$, we quickly derive the overall transmission delay $S/R_{0,a(k)} + S/R_{k,a(k)}$. By ignoring the decoding delay and queuing delay in the two-hop relaying, the throughput from the BS to GU k is given by

$$\bar{R}_k = \frac{S}{S/R_{0,a(k)} + S/R_{k,a(k)}} = \frac{R_{0,a(k)} R_{k,a(k)}}{R_{0,a(k)} + R_{k,a(k)}}. \qquad (7)$$

Therefore, the minimum throughput among GUs, i.e., $\min_k \bar{R}_k$, can be maximized by jointly designing the UAV positions $(\mathbf{x}, \mathbf{y})$ and the corresponding user assignment $a(k)$.

Moreover, to guarantee the safety requirement in UAV operations, a minimum distance D_s between UAVs should be considered. This constraint is expressed by

$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq D_s, \ \forall i, j \in \mathcal{M}, \ i \neq j. \qquad (8)$$

To sum up, the original problem of our design is formulated as

$$\text{(OP)}: \max_{\mathbf{x}, \mathbf{y}, a(k)} \quad \min_k \bar{R}_k \qquad (9)$$
$$s.t. \quad (8).$$

Note that the constraint (8) is obviously not convex. Hence, problem (OP) cannot be efficiently solved by convex technologies. Furthermore, as radio map information n_k and n_0 are involved, the objective function in problem (OP) highly depends on the concrete geographic surroundings in the deployed rectangular area. Thus, it is challenging to be solved optimally. To tackle this difficulty, we propose an efficient PSO-based design in the next section.

4. PSO-BASED DESIGN

In this section, we firstly reformulate problem (OP) based on the optimal user assignment and then solve it using PSO technologies.

4.1. Problem Reformulation based on Optimal User Assignment

With a given feasible placement of all M UAV relays, the optimal user assignment $a(k)$ can be determined in the following way. As there are no limitations on the number of GUs assigned to each relay, we independently design the assignment $a(k)$ for each GU k. To maximize the minimum $\bar{R}_k$ among GUs, the optimal assignment $a(k)$ for each GU k is achieved via maximizing the corresponding throughput $\bar{R}_k$. Otherwise, a design with a better or equal performance exists. Therefore, the optimal assignment with given $(\mathbf{x}, \mathbf{y})$ is expressed as

$$a(k) = \arg \max_{m \in \mathcal{M}} \frac{R_{0,m} R_{k,m}}{R_{0,m} + R_{k,m}}, \qquad (10)$$

The corresponding optimal throughput is given by

$$\bar{R}_k^\star(\mathbf{x},\mathbf{y}) = \max_{m\in\mathcal{M}} \frac{R_{0,m}R_{k,m}}{R_{0,m}+R_{k,m}}. \tag{11}$$

Hence, the original problem (OP) can be equivalently transformed to (P1):

$$\text{(P1)} : \max_{\mathbf{x},\mathbf{y}} \quad \min_k \bar{R}_k^\star(\mathbf{x},\mathbf{y}) \tag{12}$$
$$s.t. \quad (8).$$

4.2. PSO-based UAV Placement Algorithm

As the existence of buildings introduces a dramatic variation in radio maps with respect to the pathloss factor, the objective function in problem (P1) is not definitely differentiable in $(\mathbf{x},\mathbf{y})$. This motivated us to apply the PSO technology for the UAV placement design in problem (P1), as a PSO algorithm does not require a gradient in the optimization process [27].

First, we define an objective function $f(\mathbf{x},\mathbf{y})$ for the PSO process:

$$f(\mathbf{x},\mathbf{y}) = \begin{cases} \min_k \bar{R}_k^\star(\mathbf{x},\mathbf{y}), & \text{if (8) holds;} \\ 0, & \text{else.} \end{cases} \tag{13}$$

Note that $\min_k \bar{R}_k^\star(\mathbf{x},\mathbf{y}) > 0$ holds. Hence, as long as problem (P1) is feasible, it can be solved by maximizing $f(\mathbf{x},\mathbf{y})$. As a group of variables $(\mathbf{x},\mathbf{y})$ contains the position information of all M UAV relays, the UAVs' placement will be jointly optimized in the PSO process.

Then, the PSO process is operated with the following steps: we generate N random particles in the initialization step. For each particle $1 \le i \le N$ with position $(\mathbf{x}_i,\mathbf{y}_i)$, we record its best known position $(\mathbf{x}_i^\star,\mathbf{y}_i^\star)$ as its current position and record the corresponding best known objective as $f(\mathbf{x}_i^\star,\mathbf{y}_i^\star)$. Apparently, the current best known objective is $\max_{1\le i\le N} f(\mathbf{x}_i^\star,\mathbf{y}_i^\star)$. In addition, the velocities of particles are initialized as a zero vector $\mathbf{0}^{2M\times 1}$.

In each iteration, we update the velocity for each particle i by

$$\mathbf{v}_i \leftarrow u_0\mathbf{v}_i + u_1(\mathbf{p} - [\mathbf{x}_i^T,\mathbf{y}_i^T]^T) + u_2(\mathbf{g} - [\mathbf{x}_i^T,\mathbf{y}_i^T]^T), \tag{14}$$

where u_0 is a defined weight, while u_2 and u_3 are two generated random weights. The best known position of particle i is record in $\mathbf{p}$, i.e., $\mathbf{p} = [\mathbf{x}_i^{\star T},\mathbf{y}_i^{\star T}]^T$, while the term $\mathbf{g}$ is constructed in the same way with the current best (not best known) position among other particles. Based on the defined velocity, the position of particle i is updated as

$$[\mathbf{x}_i^T,\mathbf{y}_i^T]^T \leftarrow [\mathbf{x}_i^T,\mathbf{y}_i^T]^T + \mathbf{v}_i. \tag{15}$$

With the updated position, particle i updates its best known position $(\mathbf{x}_i^\star,\mathbf{y}_i^\star)$, if the value $f(\mathbf{x}_i,\mathbf{y}_i)$ is larger than the previous best known objective function $f(\mathbf{x}_i^\star,\mathbf{y}_i^\star)$.

By repeating the iterations, the overall best know objective function $\max_{1\le i\le N} f(\mathbf{x}_i^\star,\mathbf{y}_i^\star)$ steadily increases and will definitely converge. Finally, the algorithm will end when the following condition is satisfied within an iteration after the update of particles' positions (before the update of the best known positions of all particles):

$$0 \le \max_{1\le i\le N} f(\mathbf{x}_i,\mathbf{y}_i) - \max_{1\le i\le N} f(\mathbf{x}_i^\star,\mathbf{y}_i^\star) < \epsilon, \tag{16}$$

where ϵ is the threshold for the stopping criterion in PSO, which has a sufficiently small value. At last, the best UAV placement can be found, by comparing all the current positions $(\mathbf{x}_i,\mathbf{y}_i)$ of all particles and choosing the one providing the highest objective value $\max_{1\le i\le N} f(\mathbf{x}_i,\mathbf{y}_i)$.

Algorithm 1 : PSO-Based Design.

a) Initialize N random particles $(\mathbf{x}_i,\mathbf{y}_i)$ with $\mathbf{v}_i = \mathbf{0}^{2M\times 1}$, $1 \le i \le N$.
b) Initialize best known positions $(\mathbf{x}_i^\star,\mathbf{y}_i^\star) = (\mathbf{x}_i,\mathbf{y}_i)$, $1 \le i \le N$.
c) For each particle i, update $\mathbf{v}_i$ according to (14).
d) For each particle i, update current position $(\mathbf{x}_i,\mathbf{y}_i)$ according to (15).
e) **If** $0 \le \max_{1\le i\le N} f(\mathbf{x}_i,\mathbf{y}_i) - \max_{1\le i\le N} f(\mathbf{x}_i^\star,\mathbf{y}_i^\star) < \epsilon$
  Define UAVs' positions as the best one in current position $(\mathbf{x}_i,\mathbf{y}_i)$.
  Construct assignment according to (10).
  Return.
Else
  Update the best known position $(\mathbf{x}_i^\star,\mathbf{y}_i^\star)$ for each particle i.
  Back to c).
End

The flow of the proposed PSO-based design is summarized in Algorithm 1.

5. SIMULATION RESULTS

In this section, we provide our simulation results, which are conducted under the following parameter setups: $D_x = 350m$, $D_y = 250m$, $K = 10$, $h_0 = 10m$, $H = 30m$, $P_1 = P_2 = 1W$, $\beta_0 = -30$dB, $\sigma = -110$dBm and UAV safety distance $D_s = 2m$.

We start with Fig. 2 to investigate the radio map in terms of pathloss factor α for a single GU. The simulation is based on the map shown in Fig. 1, while the GU (red dot) is shown in Fig. 1 with index 3. It matches well with Fig. 1 (with two tall buildings around GU 3) that two areas (on the right side and the bottom of the GU) have a significant large pathloss factor. The results confirm again the effect of the geographic layout on wireless communications, and confirm the necessity of a radio map or geographic layout based design of wireless communication networks, especially with multiple users deployed at different locations.

Next, we study the convergence behaviour of the proposed design in Fig. 3 with respect to the number of calls for the objective function $f(\mathbf{x},\mathbf{y})$ calculation, as each iteration in the PSO process requires N calls for evaluation of the objective. Clearly, we find that by repeating iterations, the objective increases steadily and eventually converges. Note that as shown in Fig. 3, in some iterations the best known objective may remain unchanged, due to the fact that the current best objective may be lower than the best known one. In addition, we also compare the proposed design with exhaustive search, which searches for the best UAV placement on the basis of a defined

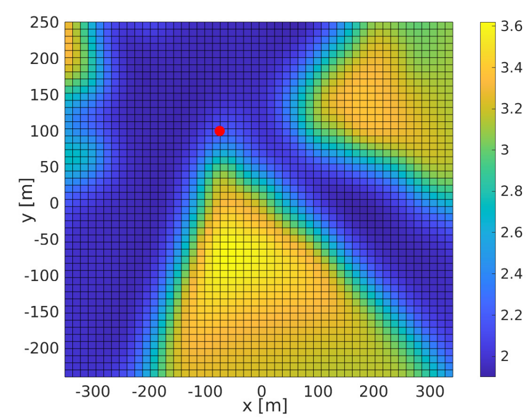

Fig. 2. Radio map of pathloss factor α for a single GU (red dot).

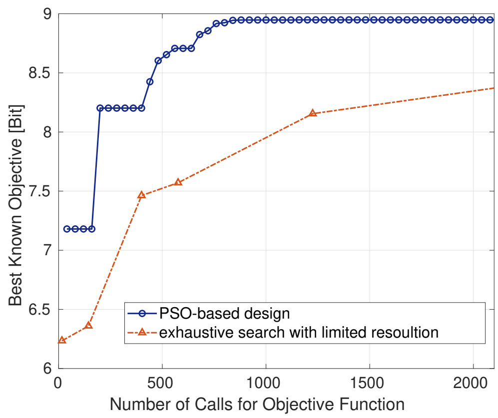

Fig. 3. Performance over different numbers of calls for objective function.

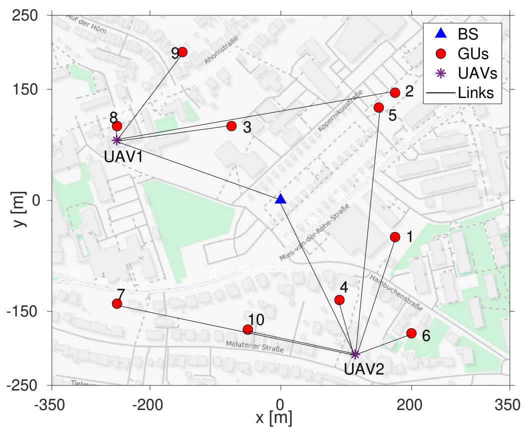

Fig. 4. Designed UAV positions and GU assignments with BS at position (0,0). (Map data from https://www.openstreetmap.org/)

resolution. We observe that to obtain the same performance, our proposed design requires fewer calculations of the objective, which implies a higher efficiency and lower complexity of our design in comparison to exhaustive search. The specific result of our design is displayed in Fig. 4 with links representing the assignment decisions. As GU 2 and GU 5 are placed in an open area, their channel qualities are relatively better than other GUs close to buildings. Hence, the optimized UAV positions tend to be closer to other GUs. In addition, GU 8 is very close to its neighbour building. To achieve a fair throughput among GUs, UAV 1 is placed to hover over the building to acquire a good channel to GU 8. In addition, the position of UAV 2 is also designed to avoid blockage on the LoS path. Moreover, we choose a different BS position and show the corresponding designed results in Fig. 5. Clearly, a different BS position results in a different solution with respect to UAV positions and user assignments.

Finally, we study the impact of the number of UAV relays on the system performance. The results are provided in Fig. 6. As more UAV relays are deployed, the minimum throughput is improved. In particular, the improvement by an additional UAV to the network is significant when less UAVs are in the system ($M = 1, 2, 3$) and is getting tiny after more UAVs are deployed ($M > 3$ or $M > 4$). Moreover, the scenario without UAV relays are also provided as a benchmark, based on which a significant performance advantage of applying UAV relays is observed. Furthermore, we learn from the figure that different BS positions influence the system performance.

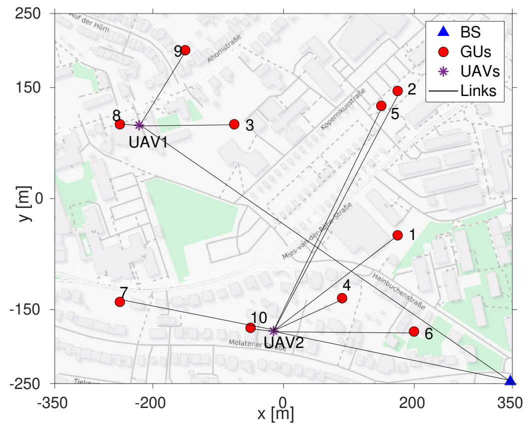

Fig. 5. Designed UAV positions and GU assignments with BS at position (350,-250).

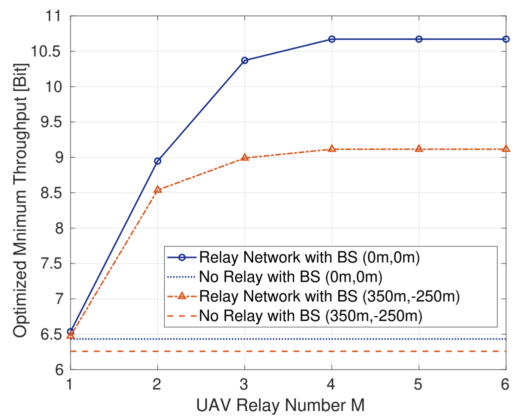

Fig. 6. Minimum throughput among GUs with different numbers of UAV relays.

In particular, a poor BS position introduces a significant performance loss with respect to the minimum throughput.

6. CONCLUSION

This paper studies a multi-UAV-assisted relaying network, where the corresponding channel pathlosses are obtained based on radio maps. A PSO-based design is proposed to jointly optimize UAVs' positions and user assignments, while aiming at maximizing the minimum throughput among GUs. As the radio maps rely on the real layout in the environment, the pathloss is neither convex nor continuous to the locations, which makes the related designs be highly difficult to analyze. To tackle this difficulty, we first reformulate the original problem based on an optimal user assignment and then apply the PSO technology to optimize the multiple-UAV placement problem while guaranteeing a minimum safety distance between UAVs. Through simulation results, the convergence of the proposed algorithm is confirmed and the performance of the design is evaluated.

7. ACKNOWLEDGEMENT

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