On Tethered UAV-assisted Heterogeneous Network

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***Abstract*—Unmanned aerial vehicle (UAV)-assisted heterogeneous network has drawn great research interests as it can significantly improve the capacity and coverage of cellular networks. An UAV can act as a flying base station (BS) or a relay when the regular terrestrial infrastructure is malfunctioned or overloaded. However, the deployment of UAV-mounted communication infrastructure is confined by the limited on-board energy and short battery life. To prolong the lifetime of each UAV, connecting it with a ground charging station (GCS) through a tether could be a promising and feasible solution. In this paper, we aim to maximize the sum rate of all users by jointly optimizing the user association, resource allocation and placement of the GCSs and the aerial UAVs. In addition, the constraint of each user's quality of service (QoS) requirement and total available resource are considered. To tackle this problem, we propose a cyclic iterative algorithm to efficiently obtain suboptimal solutions. Specifically, the primal problem is decomposed into three subproblems, i.e., the TUAV placement problem, the resource allocation problem and the user association problem. Then, the three sub-problems are alternately and iteratively optimized by using the outputs of the first two as the input for the third. Numerical experiments demonstrate that our proposed algorithm outperforms baseline algorithms under different setups.**

***Index Terms*—Tethered unmanned aerial vehicles, optimal placement, resource allocation.**

I. Introduction

Recently, unmanned aerial vehicle (UAV)-assisted [1]–[6] heterogeneous network has attracted significant attention due to its wide range of applications, such as disaster rescue and recovery, aerial camera, ground macro base station (MBS) traffic offloading [7], and communications for temporary events [8], [9]. The UAV-assisted heterogeneous network can effectively provision line of sight (LoS) communication links [10] and therefore can mitigate potential signal shadowing and blockage. The regulation relaxation and cost reduction of UAVs (especially low-cost quadcopters) as well as communication equipment miniaturization make the practical deployment of highly mobile wireless relays more feasible than before. In fact, the 3GPP Rel-16 has included UAV-enabled wireless communications in the new radio standard, aiming to boost capacity and coverage of fifth generation (5G) wireless networks [11]. Meanwhile, the approval of Federal Aviation Administration (FAA) paves the way to a large-scale deployment of UAV-enabled communications in the upcoming 5G cellular networks, especially for on-demand application scenarios.

One of the main challenges of deploying UAVs to assist the existing cellular wireless network [12]–[15] is the limited on-board energy and flight time. The current state-of-art UAVs can only stay in the air for less than one hour before battery depletion [17]. The hovering time is further reduced considering the energy consumption for the payload, communication and signal processing. The lithium-ion battery (which is widely used) energy density is expected to achieve a steady 3% performance increase per year [18], meaning that it takes roughly 24 years to double the capacity of current battery (i.e., double the flight time of a UAV from 30minutes to 1hour). Even though the capacity is doubled, it is still not enough to provide continuous service to a typical temporary event, which usually lasts severally hours. All those factors mentioned above preclude improving the battery capacity as a solution to solving the problem of UAV's limited on-board energy.

To enable the UAVs to stay in the air for a longer time, wireless power transfer (WPT) could be a promising solution. Two techniques, i.e., electromagnetic field (EMF) charging and non-EMF charging, are adopted for WPT. Specifically, the EMF charging uses electro-magnetic fields to wirelessly charge the target battery. However, these techniques suffer from low energy transferring efficiency and thus cannot provide enough energy to compensate for that consumed by the UAV. Non-EMF charging employs high-power lasers and photo-voltaic (PV) cells (which is mounted on the UAVs) to charge UAVs. The difficulty of using lasers and PV cells for energy transmission is that the transfer performance can be significantly degraded by bad weather conditions. Moreover, the receiver side may suffer from severe alignment errors because of the random fluctuation of the position and orientation of the UAVs. As a result, the amount of energy that the PV panel can collect will be dramatically reduced or diminished.

Besides all the methods mentioned above, the most practical solution to prolong UAV's flight time is to connect the UAV through a tether with a ground charging station (GCS). The GCS can provide a stable power supply and a wired backhaul link (when Internet is accessible for the GCS) while maintaining UAV's maneuverability to a certain extent. Owing to the great potential of tethered UAV (TUAV), many well-known companies have started to test TUAVs, such as AT&T's "Flying Cell-On Wings (COWS)", Facebook's "tether-Tenna", and EE's, UK's largest cellular operator, "Air Masts" [19]. The TUAV can be deployed for scenarios such as providing service to temporary events, offloading MBS which has high traffic demand and extending coverage area of an existing cellular network.

The backhaul link in a TUAV-assisted heterogeneous network should also be properly designed to avoid creating a bottleneck in the system throughput. The in-band-full-duplex approach may cause severe interference between the access link and the backhaul link as they are working on the same

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frequency band while the in-band-half-duplex approach could reduce the available bandwidth in the access link. Advances of free space optics (FSO) [30], [33] provide an alternative approach to build the connection between the MBS and the UAV. Working on the unregulated bandwidth, FSO can offer a high enough backhaul capacity to avoid bottlenecks without causing interference. FSO, as shown in Fig. 1, is deployed to serve as a dedicated backhaul from an MBS to a TUAV. In the downlink communication, the mobile data (carried in the optical beam) is sent from the FSO transmitter to the FSO receiver, mounted on the MBS and the drone base station (DBS) , respectively. The TUAV decodes the mobile data, encodes them on an radio frequency (RF) signal and finally transmits them to the corresponding ground user.

Deploying TUAVs in an existing cellular network can significantly improve the QoS of ground users without recharging as compared with deploying untethered UAVs. However, some challenges still need to be tackled.

1) How does one avoid not only the tangling between a TUAV and the surrounding buildings, but also the tangling among TUAVs?

Deploying multiple TUAVs over a given area may cause tangling among them if two GCSs are placed at a distance which is shorter than the sum of the tether lengths. In addition, the inclination angle of each tether should be high enough to avoid tangling with the surrounding buildings. Note that the minimum allowed inclination angle is coupled with the placement of TUAVs, i.e., a different minimum allowed inclination angle will result in a different placement policy. Therefore, the minimum allowed inclination angles and the locations of TUAvs should be jointly considered to maximize the sum rate in the access link.

2) What are the optimal locations of the GCSs and UAVs?

Considering the tether length, inclination angle and tangling avoidance constraint, the GCS cannot be placed at an arbitrary horizontal location. The location of the UAV is also constrained by the location of the corresponding GCS since they are connected via a tether. Therefore, it is necessary to properly determine the locations of GCSs and UAVs to prevent tangling and ensure safety.

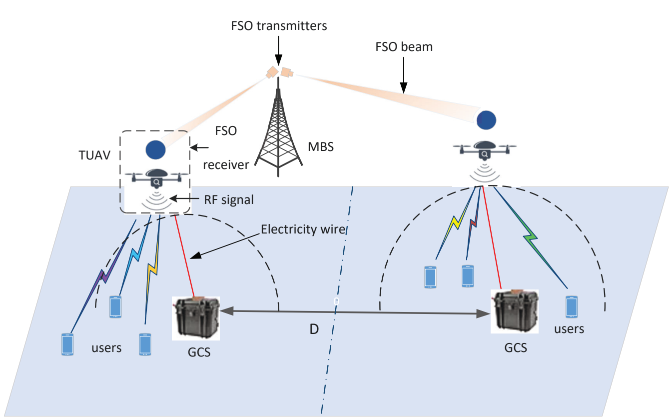

Fig. 1. TUAV-assisted heterogeneous network.

To address the above challenges, we propose a Cyclic iterAtive TUAV placeMent, usEr association and Resource Allocation (CAMERA) algorithm to maximize the sum rate in the access link with the constraints of limited available resource, tangling avoidance and user QoS requirements. The contributions of this paper include:

1) We propose a novel TUAV-assisted heterogeneous network where multiple TUAVs are deployed to work as mobile relays between the ground users and the MBS. Considering the tangling avoidance among all TUAVs, the limited available resource and user QoS requirements, we aim to maximize the throughput in the access link by optimizing the TUAV placement, user association and resource allocation.

2) To tackle the formulated problem, a cyclic iterative algorithm based on block coordinate decent method is proposed to efficiently obtain the suboptimal solutions. Specifically, the entire decision variables are partioned into three blocks, i.e., the TUAV placement, the user association and the resource allocation. Numerical simulations are conducted and the results demonstrate the effectiveness of the CAMERA algorithm and its superior performance over the baseline algorithms.

The remainder of this paper is organized as below. The related works are summarized in Section II. The system model and problem formulation are presented in Section III. In Section IV, the CAMERA algorithm based on block coordinate descent method is proposed to efficiently obtain the suboptimal solutions of the the formulated problem. Numerical results are given to demonstrate the effectiveness of the CAMERA algorithm in Section V. Finally, we conclude the paper in Section VI.

II. Related Works

There have been numerous studies about the deployment of untethered UAVs. The research efforts mainly focus on the UAV placement optimization and resource allocation. Wu *et al.* [20] considered a multi-UAV assisted wireless communications network. In the problem formulation, they aimed to maximize the minimum throughput among all users in the downlink communications by jointly optimizing the user association, the UAV's trajectory and limited transmit power. Zeng *et al.* [21] proposed to deploy a single UAV to assist the communication between a source node and a destination node where the UAV is working as a mobile relaying node. They tried to maximize the system throughput by jointly optimizing the source/relay transmit power and the UAV trajectory with practical mobility constraints. Guo *et al.* [22] proposed to recharge the UAV periodically at a fixed location to provide a seamless coverage to the users. They tried to maximize the minimum average rate among all users by jointly designing the proportion of time allocated to recharging and service, the UAV trajectory and transmit power. Huang *et al.* [23] considered a UAV-enabled wireless communications network, where device-to-device (D2D) users coexist in an underlaying way. They focused on the D2D pair rate maximization by optimizing the UAV's 3D location, bandwidth allocation among all users and transmit power of the UAV. Liu and Ansari [24] investigated the deployment of UAV-mounted base stations (UBS) in a disruptive disaster area to assist rescue where the MBS is malfunctioned. In the problem formulation, the number of human portable/wearable machine type devices (HMTDs) is maximized by optimizing the user association and resource allocation. Ali and Jamalipour [25] considered the deployment of a UAV-mounted aerial base station (ABS) which coexists with multiple terrestrial base stations (TBSs). They aimed to maximize the weighted sum of the minimum data rate of the ABS users and the minimum data rate of the TBS users. To solve the formulated non-convex problem, the block coordinate descent (BCD), the successive convex approximation (SCA), the particle swarm optimization (PSO), and the discrete search algorithm (DSA) methods are employed.

All the above works did not solve the problem of UAV's limited on-board energy essentially, including those which tried to minimize the transmit power since the amount of power consumption accounted for communications is much smaller than that for propulsion. Thus, the untethered UAV fails or has to be recharged to provide a continuous service to the users. Works related to TUAV deployment in the existing literature are very limited. Kishk *et al.* [26] studied the optimal placement of TUAVs given the tether length and the height of the surround buildings to avoid tangling and ensure safety. However, they only focused on deploying one TUAV and did not consider the resource allocation scheme and user association policy. Selim and Kamal [11] proposed to deploy tethered backhaul drone and untethered communication drone to quickly recover cellular coverage in disaster-struck areas where the existing MBS is malfunctioned. However, the untethered drones in the access link still face the problem of limited on-board energy for powering up the platform. In [27], tethered balloons work as relays among multiple high altitude platform drones and ground stations to assist the existing cellular network. In [28] , tethered balloons are used to establish backhaul links among the multiple UAVs and ground users to recover communications in a infrastructure-less environment. Pai and Sainath [29] proposed to deploy tethered UAV to assist the existing base station to improve the end-to-end performance, and they analyzed the outage probability of their proposed policy.

Different from the above works, we propose to deploy multiple TUAVs to assist the existing cellular network by determining the locations of the TUAVs and GCSs, user association and resource allocation to maximize the sum rate of all users while avoiding tangling and ensuring safety.

III. System Model

As shown in Fig. 1, we consider a TUAV-assisted heterogeneous network where the TUAVs work as relay nodes between the MBS and ground users. Our proposed framework can theoretically work for an unlimited time while maintaining UAV's maneuverability to a certain extent as compared with deploying untethered UAV. Each aerial UAV is connected to a GCS to obtain the power supply. To avoid interference among users, the frequency division multiple access (FDMA) mode is employed. The channel pathloss model, the conditions of avoiding tangling among TUAVs and the FSO-based capacity model are presented in this section. To achieve the maximum system throughput, an optimization problem subject to the user QoS requirements, limited available resource and tangling avoidance is formulated.

A. Pathloss model of the access link

Denote the set of users and the set of TUAVs as $\mathcal{I}$ and $\mathcal{J}$, respectively. We consider a Cartesian coordinate system with ground user i, GCS j and UAV j located at $(x_i, y_i, 0)$, $q_j^G = (x_j^G, y_j^G, 0)$ and $q_j^U = (x_j^U, y_j^U, H_j)$, respectively. Note that each UAV is uniquely associated with a GCS. TUAV j is assumed to fly at a fixed height H_j. Furthermore, we assume that the wireless channels in the access link are LoS-dominated. We do not constrain our application scenario to the rural area since our model can also be applied to temporary events (e.g., concerts and football matches) that are held in the urban area as long as the channels between users and UAVs are not blocked by surrounding buildings, i.e., LoS dominated. Obviously, it can also be applied to the rural area without high-rise buildings. Therefore, the down link pathloss from TUAV j to ground user i can be described by the free-space path loss model [20]

$$\xi_{ij} = \beta_0 d_{ij}^2 = \beta_0[(x_i - x_j^U)^2 + (y_i - y_j^U)^2 + H_j^2], \quad (1)$$

where β_0 denotes the pathloss at the reference distance $d = 1\ m$. With the assumption of perfect modulation, the maximum achievable data rate between ground user i and TUAV j can be expressed as

$$R_{ij} = b_i \log_2(1 + \frac{p_i}{\xi_{ij}\sigma^2}), \quad (2)$$

where b_i and p_i are the amount of bandwidth and transmit power allocated for user i, respectively. σ^2 denotes the environment noise power.

Lemma 1. *Denote L_1 and L_2 as the tether length of TUAV 1 and TUAV 2, respectively, and θ_1^{th} and θ_2^{th} as the minimum allowed inclination angle of TUAV 1 and TUAV 2, respectively. Then, the minimum distance between TUAV 1 and TUAV 2 to avoid tangling is $D^{th} = \sqrt{L_1^2 - (L_2 \sin\theta_2^{th})^2} + L_2 \cos\theta_2^{th}$.*

Proof: Fig. 2 illustrates the critical point to avoid tangling between two TUAVs, i.e., the two TUAVs might tangle with each other if the distance between them is smaller the minimum value. O_1 and O_2 are the locations of GCSs of TUAV 1 and TUAV 2, respectively, and A' and B' are the projections of A and B onto line segment O_1O_2, respectively. The circle stands for the area that the TUAV can reach. $\angle BO_1B' = \theta_1^{th}$, $\angle AO_2A' = \theta_1^{th}$, $BO_1 = L_1$, $AO_2 = L_2$. Then, the minimum distance to avoid tangling between two TUAVs can be easily obtained through Eq. (3). Here, we demonstrate the case where $L_1 \sin\theta_2^{th} < L_2 \sin\theta_2^{th}$. The case $L_1 \sin\theta_2^{th} \geq L_2 \sin\theta_2^{th}$ can be proven similarly. Thus,

$$\begin{aligned} D^{th} &= O_1O_2 = O_1A' + A'O_2 \\ &= \sqrt{L_1^2 - (L_2 \sin\theta_2^{th})^2} + L_2 \cos\theta_2^{th}. \end{aligned} \quad (3)$$

Note that this conclusion can be easily extended to the case where multiple TUAVs are deployed, i.e., any two of the deployed TUAVs should meet the requirements shown in Lemma 1. Hence, we only show the special case of two TUAVs in Lemma 1 because the conclusion can also be applied to the case of multiple TUAVs. ■

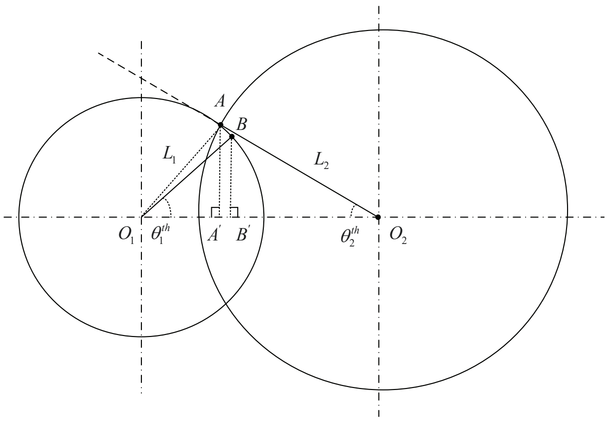

Fig. 2. Minimum distance between two TUAVs to avoid tangling.

B. FSO capacity model

We adopt FSO to facilitate the backhaul link, whose capacity can be calculated by [30], [34]:

$$C = \frac{P_t \eta_t \eta_r 10^{-\frac{L_{atm}}{10}} 10^{-\frac{L_{geo}}{10}}}{E_p N_b}, \tag{4}$$

where P_t is the transmission power of the laser, and η_t and η_r denote the transmitting efficiency and receiving efficiency, respectively. $E_p = h_p c/\lambda_c$ is the photon energy. λ_c is the carrier wavelength, h_p denotes Plank's constant. N_b reflects the receiver sensitivity (photons/bit). $L_{geo} = 10\log(\frac{\pi r^2}{\pi(\psi_t l/2)^2})$ is the geometrical loss in dB, l is the distance between the laser transmitter and receiver in Km, r is the radius of the receiver's aperture in m, and ψ_t denotes the transmitting divergence angle. $L_{atm} = \frac{17}{\Delta}(\frac{\lambda}{550nm})^{-\delta}$ stands for the atmospheric attenuation caused by bad weather conditions, where L_{atm} is in dB/Km, δ is the size distribution of the scattering particles, and Δ is the visibility in Km. The value of δ is determined by the value of the visibility distance [35]:

$$\delta = \begin{cases} 1.6, & \Delta > 50\,\text{Km} \\ 1.3, & 6\,\text{Km} < \Delta < 50\,\text{Km} \\ 0.16\Delta + 0.34, & 1\,\text{Km} < \Delta < 6\,\text{Km} \\ \Delta - 0.5, & 0.5\,\text{Km} < \Delta < 1\,\text{Km} \\ 0, & \Delta < 0.5\,\text{Km} \end{cases} \tag{5}$$

C. Problem formulation

In this section, we try to maximize the sum rate of all users while meeting the QoS requirements of users, the limited available resource and tangling avoidance among TUAVs. Specifically, the problem can be formulated as follows,

$$\textbf{P0:} \max_{\mathbf{q}_j^G, \mathbf{q}_j^U, b_i, p_i, u_{ij}} \sum_{i=1}^{|\mathcal{I}|} \sum_{j=1}^{|\mathcal{J}|} R_{ij} u_{ij} \tag{6}$$

$$s.t. \sum_{j=1}^{|\mathcal{J}|} R_{ij} u_{ij} \geq R_i^{th}, \forall i \in \mathcal{I}, \tag{7}$$

$$\sum_{i=1}^{|\mathcal{I}|} p_i u_{ij} \leq P_j^{max}, \forall j \in \mathcal{J}, \tag{8}$$

$$\sum_{i=1}^{|\mathcal{I}|} b_i \leq B, \tag{9}$$

$$||\mathbf{q}_j^G - \mathbf{q}_k^G|| \leq D^{th}, \forall j \neq k \in \mathcal{J}, \tag{10}$$

$$||\mathbf{q}_j^G - \mathbf{q}_j^U||^2 \leq L_j^2, \forall j \in \mathcal{J}, \tag{11}$$

$$\frac{H_j}{\sqrt{(x_j^U - x_j^G)^2 + (y_j^U - y_j^G)^2}} \geq \sin\theta_j^{th}, \forall j \in \mathcal{J}, \tag{12}$$

$$b_i \geq 0, \forall i \in \mathcal{I}, \tag{13}$$

$$p_i \geq 0, \forall i \in \mathcal{I}, \tag{14}$$

$$\sum_{j=1}^{|\mathcal{J}|} u_{ij} \leq 1, \tag{15}$$

$$u_{ij} = \{0, 1\}, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \tag{16}$$

where R_i^{th} denotes the data rate requirement of user i and P_j^{max} is the maximum transmission power of TUAV j. B denotes the total available bandwidth. Constraints (8) and (9) stand for the resource limitations. Constraint (10) prevents tangling between TUAVs. Constraint (11) imposes the tether length limitation. Constraint (12) ensures that the tether inclination angles are above their minimum allowed values. Constraints (13) and (14) impose resources allocated to users to be non-negative. Constraint (15) imposes one user to be associated to one TUAV at most. Constraint (16) imposes u_i to be a binary variable. Note that we omit the constraint that the backhaul capacity should be larger or equal to the traffic in the access link since an FSO link can achieve a data rate of 1-2 Gbps in the range of 1-5 Km [30].

It is challenging to solve **P0** owing to the integer decision variables. Moreover, **P0** is also a non-convex programming problem since R_{ij} is non-convex w.r.t. $\mathbf{q}_j^U$. Thus, we propose the CAMERA algorithm to efficiently obtain suboptimal solutions of the formulated problem. In essence, we partition the decision variables into three blocks, i.e., the TUAV placement, user association and resource allocation. In each iteration, firstly, given the TUAVs' locations and user association policy, we obtain the optimal resource allocation and update the objective function value. Secondly, given the TUAVs' locations and resource allocation scheme, we update the user association policy. Thirdly, given the resource allocation scheme and user association policy, we determine the TUAVs' locations. This procedure is done iteratively until the convergence criterion is met.

IV. Cyclic iterAtive TUAV placeMent, usEr association and Resource Allocation (CAMERA)

To make **P0** more tractable, we decouple the primal problem into three subproblems and optimize each subproblem alternately. We next discuss these three subproblems.

A. TUAV Placement

It is worth noting that in the TUAV placement problem, given the resource allocation scheme and user association policy, we need to not only determine the locations of the the UAVs but also the locations of GCSs. The TUAV placement problem can be expressed as

$$\mathbf{P1:}\ \max_{\mathbf{q}_j^G,\mathbf{q}_j^U} \quad \sum_{i=1}^{|\mathcal{I}|}\sum_{j=1}^{|\mathcal{J}|} R_{ij}u_{ij}$$

$$s.t.\quad \sum_{j=1}^{|\mathcal{J}|} R_{ij}u_{ij} \geq R_i^{th}, \forall i \in \mathcal{I}, \tag{17}$$

$$||\mathbf{q}_j^G - \mathbf{q}_k^G|| \leq D^{th}, \forall j \neq k \in \mathcal{J}, \tag{18}$$

$$(x_j^U - x_j^G)^2 + (y_j^U - y_j^G)^2 + H_j^2 \leq L_j^2, \forall j \in \mathcal{J}, \tag{19}$$

$$\frac{H_j}{\sqrt{(x_j^U - x_j^G)^2 + (y_j^U - y_j^G)^2}} \geq \sin\theta_j^{th}, \forall j \in \mathcal{J}. \tag{20}$$

Problem **P1** is still challenging since R_{ij} is non-concave w.r.t. $\mathbf{q}_j^G$ and $\mathbf{q}_j^U$. To solve this problem, we try to first determine the locations of the GCSs and then obtain the locations of the UAVs.

Lemma 2. *Assume the ground users follow a uniform distribution [31], [32], the optimal horizontal location of the UAV that minimizes the average path loss of all users is the geometrical center of the area.*

Proof: Since the ground users are uniformly scattered in the square area shown in Fig. 1, the probability distribution function (pdf) of a given user in location $(x, y, 0)$ is

$$f(x,y) = \begin{cases} \frac{1}{4LW}, & \text{if } |x| \leq L, |y| \leq W, \\ 0, & \text{otherwise}, \end{cases} \tag{21}$$

where $2L$ and $2W$ are the length and width of the area, respectively. Thus, the average path loss of all users can be calculated by

$$E(\xi) = \iint_{|x|\leq L,|y|\leq W} (\frac{1}{4LW} \cdot \xi)\ dxdy \tag{22}$$

$$\stackrel{a}{=} \iint_{|x|\leq L,|y|\leq W} \{\frac{\beta_0}{4LW}[H^2 + (x - x^U)^2 + (y - y^U)^2]\}\ dxdy$$

$$= \beta_0[H^2 + \frac{1}{3}L^2 + \frac{1}{3}W^2 + (x^U)^2 + (y^U)^2] \tag{23}$$

$$\stackrel{b}{\geq} \beta_0(H^2 + \frac{1}{3}L^2 + \frac{1}{3}W^2)$$

where step (a) is derived by substituting Eq. (1) into Eq. (22), and the equality condition in step (b) holds when $x^U = 0$ and $y^U = 0$ (i.e., the geometrical center of the square area). We can observe from Eq. (23) that the average path loss of all users is an increasing function of the distance between the UAV and the geometrical center of the square area. ■

Based on Lemma. 2, we place each GCS around the geometrical center of the area by setting the distance between every two successive GCSs to be D^{th} as shown in Fig. 3 for an example with 4 TUAVs. It is worth noting that Lemma 2 is derived based on the intuition that a smaller pathloss yields a higher data rate. We place the GCSs based on Lemma 2 to ensure that the aerial UAVs can reach the geometrical centers. Note that the aerial UAVs may not be able to be deployed at the geometrical centers if the GCSs are placed too far away from the geometrical centers as they are confined by the tether. Also, the optimal locations of the aerial UAVs may not necessarily be the geometrical centers; they are further adjusted to maximize the sum rate of all users by searching the candidate locations in the horizontal plane.

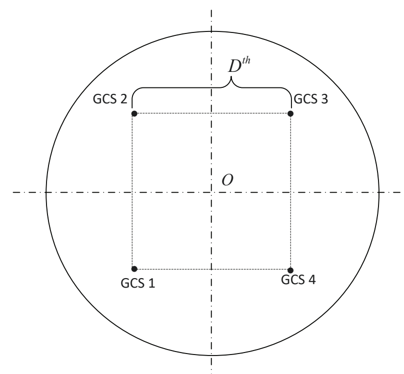

Fig. 3. An example of GCS placement.

Given locations of the GCSs (i.e., given x_j^G and y_j^G), **P1** can be rewritten as

$$\mathbf{P1\text{-}a:}\ \max_{\mathbf{q}^U} \quad \sum_{i=1}^{|\mathcal{I}|}\sum_{j=1}^{|\mathcal{J}|} R_{ij}u_{ij}$$

$$s.t.\quad (x_j^U - x_i)^2 + (y_j^U - y_i)^2 \leq \frac{p_i}{\sigma^2\beta_0(2^{R_i^{th}/b_i} - 1)} - H_j^2, \forall i \in \mathcal{I}, \tag{24}$$

$$(x_j^U - x_j^G)^2 + (y_j^U - y_j^G)^2 \leq L_j^2 - H_j^2, \forall j \in \mathcal{J}, \tag{25}$$

$$(x_j^U - x_j^G)^2 + (y_j^U - y_j^G)^2 \leq \frac{H_j^2}{\sin^2\theta_j^{th}}, \forall j \in \mathcal{J}. \tag{26}$$

Note that in **P1-a**, variables q_1^U to $q_{|\mathcal{J}|}^U$ are independent of each other. Thus, we can solve problem **P1-a** by solving $|\mathcal{J}|$ independent subproblems, i.e.,

$$\mathbf{P1\text{-}b:}\ \max_{q_j^U} \quad \sum_{i=1}^{|\mathcal{I}|} R_{ij}u_{ij}$$

$$s.t.\quad (x_j^U - x_i)^2 + (y_j^U - y_i)^2 \leq \frac{p_i}{\sigma^2\beta_0(2^{R_i^{th}/b_i} - 1)} - H_j^2, \forall i \in \mathcal{I}, \tag{27}$$

$$(x_j^U - x_j^G)^2 + (y_j^U - y_j^G)^2 \leq L_j^2 - H_j^2, \tag{28}$$

$$(x_j^U - x_j^G)^2 + (y_j^U - y_j^G)^2 \leq (\frac{H_j}{\sin\theta_j^{th}})^2. \tag{29}$$

Lemma 3. *Problem **P1-a** is neither a convex nor a concave optimization problem.*

Proof: Note that **P1-a** can be proven to be neither a convex nor a concave optimization problem if R_{ij} is neither a convex nor a concave function w.r.t. x_j^U or y_j^U. Since R_{ij} shares the same convexity with function $f = \log(1+1/(x^2+y^2+H^2))$, we next study the convexity of f instead of R_{ij} for simplicity. Note that f can be rewritten as a composition function of x and y, i.e.,

$$f = h(g(x,y)), \tag{30}$$

where $h(x) = \log(1+\frac{1}{x})$ and $g(x,y) = x^2+y^2+H^2$. The second derivative of the composition function $f = h(g(x,y))$ can be calculated by

$$f''(x) = h''(g(x))g'(x)^2 + h'(g(x))g''(x) = \frac{2\left(3x^4+\left(2y^2+2h^2+1\right)x^2-y^4-\left(2h^2+1\right)y^2-h^4-h^2\right)}{\left(x^2+y^2+h^2\right)^2\left(x^2+y^2+h^2+1\right)^2}.$$

Note that $f''>0$ (i.e., f is a convex function) when the value of x is sufficiently large and that of y is sufficiently small, and $f''<0$ (i.e., f is a concave function) when the value of x is sufficiently small and that of y is sufficiently large, thus leading to **P1-b** being neither a convex nor a concave optimization problem. ■

To solve **P1-b**, we first divide a given area into several candidate locations with the same size and then obtain the UAV's location by utilizing the exhaustive method. UAV j is finally placed at the location which incurs the maximum value of the objective function (i.e., the sum rate). Note that the number of the squares (i.e., candidate locations of the aerial UAVs) is limited; the complexity of our method therefore incurs limited complexity. Specifically,

1) We divide the coverage area into a number of locations with the same size. Denote $\mathcal{K}$ as the set of these locations and k as the index of these locations. These locations would be the candidate locations that the UAV can be placed (note that the longitude and latitude of the DBS can be obtained based on the corresponding location index).

2) We exhaustively search all candidate locations with the fixed flying height of H_j. The optimal location index k^* will be the one which which incurs the maximum value of $\sum_{i=1}^{|\mathcal{I}|} R_{ij}u_{ij}$, i.e.,

$$k^* = \arg\max_k \left\{ \sum_{i=1}^{|\mathcal{I}|} R_{ij}u_{ij} \mid (27),(28),(29), k\in\mathcal{K} \right\}. \tag{31}$$

B. Resource Allocation

Given the TUAVs' locations and user association policy, we try to maximize the throughput in the access link via optimizing the resource allocation. The primal problem can thus be reduced to

$$\textbf{P2:} \max_{b_i,p_i} \sum_{i=1}^{|\mathcal{I}|}\sum_{j=1}^{|\mathcal{J}|} R_{ij}u_{ij}$$

$$\text{s.t.} \sum_{j=1}^{|\mathcal{J}|} R_{ij}u_{ij} \geq R_i^{th}, \forall i\in\mathcal{I}, \tag{32}$$

$$\sum_{i=1}^{|\mathcal{I}|} p_i u_{ij} \leq P_j^{max}, \forall j\in\mathcal{J}, \tag{33}$$

$$\sum_{i=1}^{|\mathcal{I}|} b_i \leq B, \tag{34}$$

$$b_i \geq 0, \forall i\in\mathcal{I}, \tag{35}$$

$$p_i \geq 0, \forall i\in\mathcal{I}. \tag{36}$$

Lemma 4. ***P2** is a concave optimization problem.*

Proof: We can observe that **P2** is a concave optimization problem if R_{ij} is a concave function of b_i and p_i since Constraints (33), (34), (35) and (36) are all linear functions. It is worth noting here that the summation in the objective function does not influence the convexity of **P2**. The Hessian matrix of R_{ij} w.r.t. b_i and p_i can be derived as

$$\nabla^2 R_{ij} = \begin{bmatrix} 0, & \frac{1}{(p_i+\alpha_{ij})\ln 2} \\ \frac{1}{(p_i+\alpha_{ij})\ln 2}, & -\frac{b_i}{(p_i+\alpha_{ij})^2\ln 2} \end{bmatrix}, \tag{37}$$

where $\alpha_{ij} = \sigma^2\beta_0((x_j^U-x_i)^2+(y_j^U-y_i)^2+H_j^2)$. Since b_i, p_i and α_{ij} are positive, $\nabla^2 R_{ij}$ is negative semidefinite, which indicates that R_{ij} is concave w.r.t. b_i and p_i. ■

Since **P2** has been proven to be a concave optimization problem, we can utilize CVX or CPLEX to obtain its optimal solutions.

C. User Association

In the user association problem, given the TUAVs' locations and resource allocation, we determine the user association policy to maximize the sum rate of all users by solving the following optimization problem:

$$\textbf{P3:} \max_{u_{ij}} \sum_{i=1}^{|\mathcal{I}|}\sum_{j=1}^{|\mathcal{J}|} R_{ij}u_{ij}$$

$$\text{s.t.} \sum_{j=1}^{|\mathcal{J}|} R_{ij}u_{ij} \geq R_i^{th}, \forall i\in\mathcal{I}, \tag{38}$$

$$\sum_{i=1}^{|\mathcal{I}|} p_i u_{ij} \leq P_j^{max}, \forall j\in\mathcal{J}, \tag{39}$$

$$\sum_{j=1}^{|\mathcal{J}|} u_{ij} \leq 1, \tag{40}$$

$$u_{ij} = \{0,1\}, \forall i\in\mathcal{I}, \forall j\in\mathcal{J}. \tag{41}$$

Note that **P3** is a Generalized Assignment Problem (GAP) problem, where user i and TUAV j are mapped to item i and knapsack j, respectively. Thus, R_{ij} is the profit of item i if assigned to knapsack j, p_i is the weight of item i and P_j^{max} is the capacity of knapsack j. The optimal solution of **P3** can be obtained through depth-first branch-and-bound method [36].

We summarize the steps of the CAMERA algorithm in Algorithm 1. Line 1 initializes all parameters. The complexity of line 3 is $O(|\mathcal{K}||J|)$, that of line 4 is $O(|\mathcal{I}|)$, that of line 5 is $O(|\mathcal{I}||\mathcal{J}|^2)$ in the worst case [36], lines 3-5 can repeat for no more than $|\mathcal{K}|$ times. Hence, the complexity of CAMERA is $O(|\mathcal{K}|^2|\mathcal{J}| + |\mathcal{K}||\mathcal{I}||\mathcal{J}|^2)$.

Algorithm 1

1: Initialize $\mathbf{q}^{G^{(0)}}$, $\mathbf{q}^{U^{(0)}}$,$b_i^{(0)}$, $p_i^{(0)}$, $u_{ij}^{(0)}$. Set the iteration number n=1.
2: **while** the value of Eq. (6) increases **do**
3: Given $b_i^{(n-1)}$, $p_i^{(n-1)}$ and $u_{ij}^{(n-1)}$, obtain $\mathbf{q}^{G^{(n)}}$ and $\mathbf{q}^{U^{(n)}}$ by solving **P1**;
4: Given $\mathbf{q}^{G^{(n)}}$, $\mathbf{q}^{U^{(n)}}$ and $u_{ij}^{(n-1)}$, acquire the optimal $b_i^{(n)}$ and $p_i^{(n)}$ by solving **P2**;
5: Given $\mathbf{q}^{G^{(n)}}$, $\mathbf{q}^{U^{(n)}}$, $b_i^{(n)}$ and $p_i^{(n)}$, obtain the optimal $u_{ij}^{(n)}$ by solving **P3**;
6: Set the iteration number n=n+1;
7: **end while**
8: Output $\mathbf{q}^{G^*} = \mathbf{q}^{G^{(n)}}$, $\mathbf{q}^{U^*} = \mathbf{q}^{U^{(n)}}$, $b_i^* = b_i^{(n)}$, $p_i^* = p_i^{(n)}$ and $u_{ij}^* = u_{ij}^{(n)}$.

V. Simulations

In this section, we provide numerical results to evaluate the performance of CAMERA. Here, two TUAVs are deployed over a rectangle area with the size of 1000 m $\times$ 500 m. The flying heights of two TUAVs are $H_1 = H_2 = 100$ m. The ground users are uniformly distributed in the area. The size of each location k in the given area is 10 m by 10 m. Users' data rate requirements are generated based on the Poisson distribution with the expectation of 50 Kbps. For simplicity, we summarize other simulation parameters in Table I. Next, we compare the performance of CAMERA with the following two schemes: 1) Stationary DBS, where the DBS is placed at the geometrical center with the flying height $h = 100m$. Meanwhile, the bandwidth is equally allocated to all users. 2) MBS only, where no DBS is deployed to assist the MBS in the existing cellular network. In this scheme, all users are directly connected to the MBS without a relay with equally allocated resource. The MBS is located at $(500, 500)$.

Fig. 4 shows the sum rate of all users of the TUAV scheme, stationary DBS scheme and MBS only scheme, respectively. From Fig. 4, we can see the sum rate of all users of our proposed approach outperforms that of the stationary DBS approach by nearly 50%. Both schemes with relays outperform the 'MBS only' scheme since a better channel condition is provided. Furthermore, as shown in the figure, the sum rate of all approaches decreases as the number of users increases. This is because as the number of users increases, more resources have to be allocated to users that experience worse channel conditions, and thus less resources are left for the users that have better channel conditions. To achieve the maximal sum rate, all the remaining resources (after user QoS requirements are met) should be allocated to the user that has the best channel condition. With the increase of users, more resources need to be allocated to the newly emerging users to guarantee their QoS, thus leading to a decrease of the sum rate of all users.

TABLE I
Simulation Parameters

Parameters	Definition	Value
σ^2	Noise power	-140 dBm
B	Total available bandwidth	20 MHz
P^D	Transmit power of DBS	0.5 mW
P^M	Transmit power of MBS	1 mW
P_j^{max}	Transmit power of TUAV 1, 2	0.5 mW
θ_j^{th}	Minimum allowed inclination angle	$\pi/3$ rad
L_j	Tether length of TUAV 1, 2	120 m
D^{th}	Minimum distance to avoid tangling	120 m

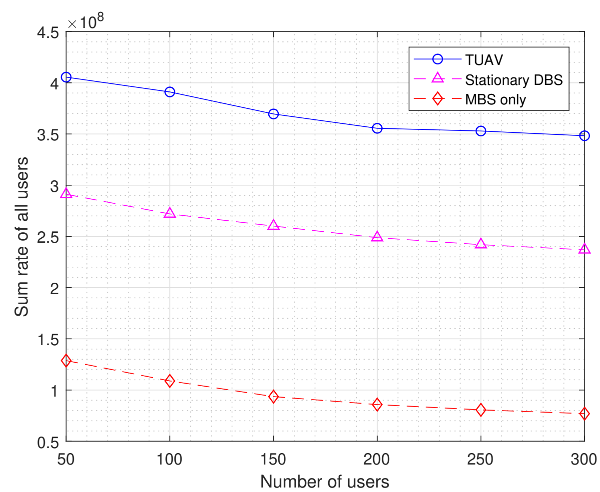

Fig. 4. Sum rate of all users versus number of users.

Figs. 5 and 6 illustrate the sum rate of all users versus the total available resource, i.e., the total available bandwidth and transmit power, respectively. It is observed that as the total available resource increases, the sum rate of all users increases in all three schemes. This is due to the fact that the sum rate is an increasing function of allocated bandwidth and transmit power. In addition, our proposed TUAV scheme achieves better performance as compared to the other two baseline algorithms. The rationale behind is that our proposed scheme can improve the sum rate of all users by adjusting the UAVs' locations (as compared with stationary DBS) and allocating more resource to the users which have better channel conditions (as compared with equal resource allocation). It is also observed that both schemes with relays outperform the MBS only scheme since better wireless channels are provided for the ground users as compared with directly connecting to the MBS.

Figs. 5 and 6 also show the gap between each scheme. For instance, given the total available bandwidth is 22MHz, the sum rates of the 'MBS only' scheme, the 'Stationary DBS' scheme and the proposed scheme are 132Mbps, 319Mbps and 422 Mbps, respectively. We can see that the sum rate of the users is increased by 141.7% by introducing a stationary DBS into an MBS only wireless network because the favorable Line of Sight (LoS) connection can be established between the users and the DBS. In comparison, the increase obtained from the 'Stationary DBS' scheme to the TUAV scheme is not as significant as the increase obtained from the 'MBS only' scheme to the 'Stationary DBS' scheme. This is because the 'Stationary DBS' scheme and the TUAV scheme share the same pathloss model and the gain is limited by adjusting the locations of the UAVs.

Furthermore, our proposed approach can theoretically provide unlimited time service to the users, while a DBS without charging can last for no more than 1 hour [17].

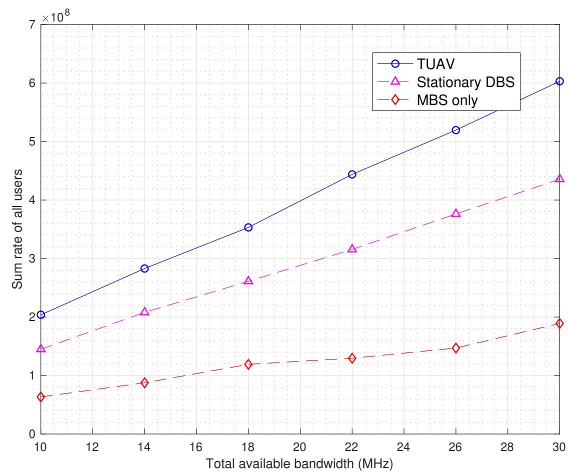

Fig. 5. Sum rate of all users versus total available bandwidth.

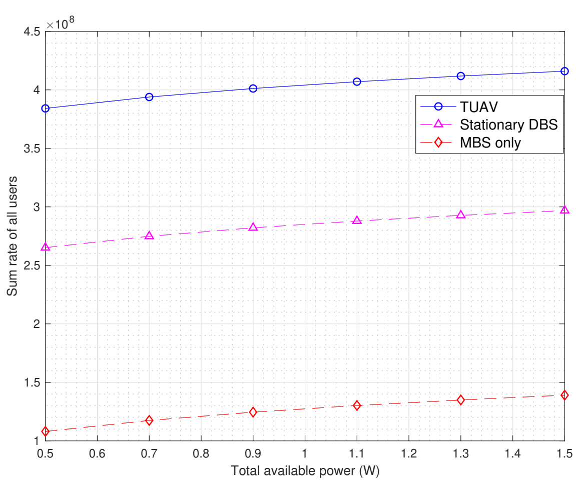

Fig. 6. Sum rate of all users versus total available power.

VI. Conclusion

In this paper, we have studied a TUAV-enabled heterogeneous network where multiple TUAVs are deployed to assist the MBS to serve the ground users. We have formulated the multiple TUAV placement, the resource allocation and the user association problem as an the optimization problem, which maximizes the sum rate of all users subject to the constraints of user QoS requirements, tangling avoidance and limited available resource. The CAMERA algorithm is designed to efficiently solve the formulated problem. The performance of the CAMERA algorithm has been demonstrated via numerical results.

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