UAV Trajectory Optimization for Data Offloading at the Edge of Multiple Cells

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***Abstract*—In future mobile networks, it is difficult for static base stations (BSs) to support the rapidly increasing data services, especially for cell-edge users. Unmanned aerial vehicle (UAV) is a promising method that can assist BSs to offload the data traffic, due to its high mobility and flexibility. In this paper, we focus on the UAV trajectory at the edges of three adjacent cells to offload traffic for BSs. In the proposed scheme, the sum rate of UAV served edge users is maximized subject to the rate requirements for all the users, by optimizing the UAV trajectory in each flying cycle. The optimization is a mixed-integer non-convex problem, which is difficult to solve. Thus, it is transformed into two convex problems, and an iterative algorithm is proposed to solve it by optimizing the UAV trajectory and edge user scheduling alternately. Simulation results are presented to show the effectiveness of the proposed scheme.**

***Index Terms*—Data offloading, interference avoidance, trajectory optimization, unmanned aerial vehicle (UAV).**

I. Introduction

Future mobile networks aim to realize larger coverage, support more devices, and achieve higher throughput to meet the explosive by increasing demand for data [1], [2]. However, the traditional cellular networks are deployed typically with static base stations (BSs), which have several challenges. First, the pressure on BSs is becoming more and more serious with increasing data traffic. Moreover, edge users often suffer from poor quality of service (QoS) due to long distances from BSs. As a result, there has been growing interest in hybrid cellular networks assisted by unmanned aerial vehicle (UAV) as mobile BSs [3], due to their mobility and flexibility.

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UAVs can not only help ground BSs to offload data traffic, but also enhance the channel conditions of edge users by flying close to them to provide line-of-sight (LOS) links [4]. Furthermore, there have been many other wireless applications for UAVs, such as mobile relays [5], [6], mobile computing cloudlets [7], *etc*. Some important works have been conducted in UAV-aided mobile networks recently [8]–[18]. In [8], Bor-Yaliniz *et al.* investigated the 3-D placement problem of the static UAV to maximize the covered number of users. The 2-D placement optimization algorithm of multiple UAVs was proposed by Lyu *et al.* in [9], to minimize the number of UAVs that can cover all the ground terminals. Mozaffari *et al.* maximized the downlink coverage significantly by optimizing 3D deployment of UAVs with directional antennas in [10]. In [11], the sum rate was effectively maximized by Mozaffari *et al.* through appropriately adjusting the UAV's altitude based on the density of D2D users. In [12], Chen *et al.* deployed cache-enabled UAVs in the cloud radio access networks to optimize the quality of experience for mobile users. In [13], a caching UAV assisted secure transmission scheme in small-cell networks based on interference alignment was proposed by Cheng *et al.*. The energy trade-off problem in the ground-to-UAV communications was studied by Yang *et al.* via trajectory optimization in [14]. In [15], Lyu *et al.* maximized the minimum rate of all mobile terminals by jointly optimizing the UAV's circular trajectory radius, user partitioning and bandwidth allocation. The UAV trajectory optimization is difficult to solve due to the non-convexity, and some pioneering work was done by Zeng *et al.* to first utilize successive convex optimization to solve the problem effectively [16] and [17]. In [18], some fundamental research was done by Wu *et al.*, in which multiple UAVs' trajectories were optimized jointly with the user scheduling and power allocation, to maximize the minimum rate of all the mobile users. Nevertheless, no ground BSs were considered in [18], but the interference between BSs and UAV will affect the QoS of mobile users severely, which should be properly avoided by optimizing the UAV trajectory.

Motivated by this, in this paper, we study a hybrid cellular network with UAV-aided offloading at the edges of multiple cells, by accounting for the interference between ground BSs and UAV. In the proposed scheme, the UAV trajectory is optimized to maximize the sum rate of edge users by avoiding the interference effectively, with the rate requirements of all the users guaranteed. This mixed-integer non-convex problem is difficult to solve, and thus, an iterative algorithm is proposed to obtain sub-optimal solutions by optimizing the convex UAV trajectory and edge user scheduling alternately. Finally,

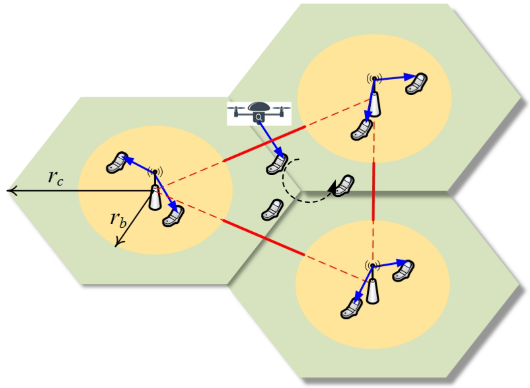

Fig. 1. UAV data offloading at the edge of three adjacent cells.

simulation results are presented to show the effectiveness of the proposed UAV trajectory scheme with the existence of multiple BSs.

Notation: Italic letter a or A denotes that it is a scalar, and bold-face lower-case letter $\mathbf{a}$ and bold-face upper-case letter $\mathbf{A}$ denote a vector and a matrix, respectively. $\mathbf{a}^T$ represents its transpose and $\|\mathbf{a}\|$ denotes its Euclidean norm.

II. System Model and Problem Formulation

A. System Model

Consider a cellular network with three adjacent BSs[1] and a single UAV jointly serving the ground users, as shown in Fig. 1. The users are randomly distributed in each hexangular cell with radius r_c. Each BS is located at the center of its cell. To guarantee the QoS of edge users, each BS only serves the users within the distance r_b, $r_b \le \frac{\sqrt{3}}{2} r_c$, while the remaining edge users of three adjacent cells served by the UAV. The sets of users served by the mth BS and the UAV are denoted as $\mathcal{I}_m$ and $\mathcal{K}$, respectively, $m = 1, 2, 3$. Each BS has M antennas, while the UAV and each mobile user have a single antenna [4]. Assume that there is no interference between the users served by different BSs, due to the long distance. The Cartesian coordinate system is considered, where the horizontal coordinates of the mth BS, the ith user served by the mth BS and the kth user served by the UAV are expressed as $\mathbf{G}_m$, $\mathbf{W}_{mi}$ and $\mathbf{W}_k$, respectively.

We assume that the UAV flies at a fixed altitude H above ground within each cycle T, which can be divided into N equivalent time slots. The value of N should be properly chosen to guarantee that the UAV's location is approximately unchanged within each slot. H should be set as small as possible with the safety considerations such as terrain or building avoidance. Then, the horizontal location of the UAV at the nth time slot can be denoted as $\mathbf{q}[n] = [x[n], y[n]]^T$, $n = 1, 2, ..., N$. The maximum UAV speed is denoted as V, and thus, the UAV trajectory should satisfy

$$\mathbf{q}[1] = \mathbf{q}[N], \tag{1}$$

$$||\mathbf{q}[n+1] - \mathbf{q}[n]||^2 \le \left(\frac{VT}{N}\right)^2, n = 1, 2, \cdots, N-1. \tag{2}$$

[1]The proposed scheme can be easily extended to general cases with more adjacent cells considered.

The channel power gain from the UAV to the user located at $\mathbf{W}_l$ ($l = mi$ or k) is assumed to follow the free-space path loss model due to LOS channel as

$$h_{ul} = \rho_0 \left(H^2 + \|\mathbf{q}[n] - \mathbf{W}_l\|^2\right)^{-1}, n = 1, 2, \cdots, N, \tag{3}$$

where ρ_0 is the reference channel power at $d_0 = 1$ m. The channel power gain from the mth BS to the ith user served by the BS can be denoted as

$$h_{mi} = \alpha_0 \left|\bar{\mathbf{h}}_{mm}^{[i]} \mathbf{v}_m^{[i]}\right|^2 \left(\|\mathbf{G}_m - \mathbf{W}_{mi}\|^2\right)^{-3/2}, \tag{4}$$

where α_0 is the reference terrestrial channel power gain, the path loss exponent of terrestrial channels is assumed to be 3, and $\bar{\mathbf{h}}_{mm}^{[i]}$ accounts for the small-scale channel fading from the mth BS to the ith user served by the BS. $\mathbf{v}_m^{[i]}$ is the precoding vector for the ith user served by the mth BS, which is designed to eliminate the interference between users served by the BS.

The UAV offloading schedule is defined as

$$\alpha_k[n] = \{0, 1\}, \forall k \in \mathcal{K}, \forall n, \tag{5}$$

where $\alpha_k[n] = 1$ (or 0) indicates that the UAV serves (or does not serve) the kth edge user in the nth time slot. Assume that the UAV can serve at most one edge user in each time slot, which yields the constraint as

$$\sum\nolimits_{k \in \mathcal{K}} \alpha_k[n] \le 1, \ \forall n. \tag{6}$$

B. Problem Formulation

According to the system model in Section II-A, the average rate of the ith user served by the mth BS ($m = 1, 2, 3$) over N time slots can be expressed as

$$R_m^{[i]} = \frac{1}{N} \sum_{n=1}^{N} \log_2 \left(1 + \frac{P h_{mi}}{p_u h_{umi} + \sigma^2}\right), \forall i \in \mathcal{I}_m, \tag{7}$$

where P and p_u are the transmit power of each BS and the UAV, respectively, and σ^2 is the additive white Gaussian noise power.

The average rate of the kth edge user served by the UAV over N time slots can be expressed as

$$R^{[k]} = \frac{1}{N} \sum_{n=1}^{N} \alpha_k[n] \log_2 \left(1 + \frac{p_u h_{uk}}{I_u^{[k]} + \sigma^2}\right), \forall k \in \mathcal{K}, \tag{8}$$

where

$$I_u^{[k]} = \sum_{m=1}^{3} \frac{P\rho_0}{\|\mathbf{G}_m - \mathbf{W}_k\|^2} \left(\sum_{i \in \mathcal{I}_m} \left|\bar{\mathbf{h}}_{mu}^{[k]} \mathbf{v}_m^{[i]}\right|^2\right) \tag{9}$$

is the interference to the kth edge user served by UAV from the BSs. $\bar{\mathbf{h}}_{mu}^{[k]}$ accounts for small-scale channel fading from the mth BS to the kth edge user served by the UAV. Thus, the sum rate of users served by the UAV can be written as

$$R_u^{sum} = \sum\nolimits_{k \in \mathcal{K}} R^{[k]}. \tag{10}$$

Assume that the transmission rate of each user served by the BS and each user served by the UAV should be higher than or equal to γ and η, respectively. Our goal is to maximize the sum rate of all the edge users served by the UAV with the minimum rate requirement at each user by jointly optimizing the edge user scheduling $\mathbf{A}=\{\alpha_k[n],\forall k,\forall n\}$ and UAV trajectory $\mathbf{Q}=\{\mathbf{q}[n],\forall n\}$. The optimization problem can be formulated as

$$\max_{\mathbf{A},\mathbf{Q}} R_u^{sum} \tag{11a}$$
$$s.t.\ R^{[k]} \geq \eta,\ \forall k\in\mathcal{K}, \tag{11b}$$
$$R_m^{[i]} \geq \gamma,\ \forall i\in\mathcal{I}_m, \forall m\in\{1,2,3\}, \tag{11c}$$
$$(1),(2),(5),(6). \tag{11d}$$

III. Low-Complexity Solution

Problem (11) is difficult to solve as it is a mixed-integer non-convex problem. To make it tractable, the binary variables in (5) are relaxed into continuous variables as

$$0\leq \widehat{\alpha}_k[n]\leq 1, \forall k\in\mathcal{K},\forall n. \tag{12}$$

Then, an efficient iterative algorithm is proposed. In each iteration, the edge user scheduling is first optimized for fixed UAV trajectory, and then, UAV trajectory is optimized with the optimized user scheduling in the first step.

A. Edge User Scheduling Optimization

For any given UAV trajectory $\mathbf{Q}$, the edge user scheduling optimization in (11) can be rewritten as follows, with $\alpha_k[n]$ relaxed into continuous $\widehat{\alpha}_k[n]$.

$$\max_{\mathbf{A}} R_u^{sum} \tag{13a}$$
$$s.t.\ R^{[k]} \geq \eta,\ \forall k\in\mathcal{K}, \tag{13b}$$
$$(6),(12). \tag{13c}$$

Problem (13) is easy to solve by applying classical optimization methods, because it is a standard linear programming.

B. UAV Trajectory Optimization

For any given edge user scheduling $\mathbf{A}$, the UAV trajectory optimization in (11) can be rewritten as

$$\max_{\mathbf{Q}} R_u^{sum} \tag{14a}$$
$$s.t.\ R^{[k]} \geq \eta,\ \forall k\in\mathcal{K}, \tag{14b}$$
$$R_m^{[i]} \geq \gamma,\ \forall i\in\mathcal{I}_m, \forall m\in\{1,2,3\}, \tag{14c}$$
$$(1),(2). \tag{14d}$$

Note that (14) is not a convex optimization problem due to the non-convex objective function and the non-convex constraints in (14b) and (14c), which is difficult to solve. Therefore, a successive convex optimization technique is applied to obtain the optimal solution approximately, which can be derived in Theorem 1. To obtain Theorem 1, Lemma 1 and Lemma 2 are first introduced to make constraints (14b) and (14c) convex.

Lemma 1: The non-convex constraint (14b) can be transformed into a convex one as

$$\frac{1}{N}\sum_{n=1}^{N}\widehat{\alpha}_k[n]\widehat{R}_{ulb}^{[k]}[n]\geq\eta,\ \forall k\in\mathcal{K}, \tag{15}$$

where

$$\widehat{R}_{ulb}^{[k]}[n]=-C_k^r[n]\left(\|\mathbf{q}[n]-\mathbf{W}_k\|^2-\|\mathbf{q}^r[n]-\mathbf{W}_k\|^2\right)+D_k^r[n], \tag{16}$$

$$C_k^r[n]=\frac{\frac{\left(I_u^{[k]}+\sigma^2\right)p_u\rho_0}{\left(\left(I_u^{[k]}+\sigma^2\right)\left(H^2+\|\mathbf{q}^r[n]-\mathbf{W}_k\|^2\right)\right)^2}\log_2(e)}{1+\frac{p_u\rho_0}{\left(I_u^{[k]}+\sigma^2\right)\left(H^2+\|\mathbf{q}^r[n]-\mathbf{W}_k\|^2\right)}}\geq 0, \tag{17}$$

$$D_k^r[n]=\log_2\left(1+\frac{p_u\rho_0}{\left(I_u^{[k]}+\sigma^2\right)\left(H^2+\|\mathbf{q}^r[n]-\mathbf{W}_k\|^2\right)}\right)\geq 0. \tag{18}$$

Proof: First, we can define $\widehat{R}_u^{[k]}[n]$ as

$$\widehat{R}_u^{[k]}[n]=\log_2\left(1+\frac{p_u\rho_0}{\left(I_u^{[k]}+\sigma^2\right)\left(H^2+\|\mathbf{q}[n]-\mathbf{W}_k\|^2\right)}\right). \tag{19}$$

It is important to observe that $\widehat{R}_u^{[k]}[n]$ is convex with respect to $\|\mathbf{q}[n]-\mathbf{W}_k\|^2$, although it is not concave with respect to $\mathbf{q}[n]$. Then, we assume that $\mathbf{Q}^r=\{\mathbf{q}^r[n],\forall n\}$ is the trajectory of UAV in the rth iteration. It is known that the first-order Taylor series expansion of a convex function provides a lower bound. Thus, with given UAV trajectory $\mathbf{Q}^r$ in the rth iteration, we have (20) in the $(r+1)$th iteration as follows.

$$\begin{aligned}\widehat{R}_u^{[k]}[n]&\geq -C_k^r[n]\left(\|\mathbf{q}[n]-\mathbf{W}_k\|^2-\|\mathbf{q}^r[n]-\mathbf{W}_k\|^2\right)+D_k^r[n]\\&=\widehat{R}_{ulb}^{[k]}[n],\end{aligned} \tag{20}$$

where $C_k^r[n]$ and $D_k^r[n]$ are constants as in (17) and (18).

Therefore, the non-convex constraint (14b) can be approximated as (15). Since $\widehat{R}_{ulb}^{[k]}[n]$ is concave with respect to $\mathbf{q}[n]$, the constraint (15) is convex with respect to $\mathbf{q}[n]$. ■

Lemma 2: By using the successive convex optimization technique and introducing slack variables $\mathbf{S}=\{S_{mi}[n],\forall i\in\mathcal{I}_m,\forall m\in\{1,2,3\},\forall n\}$, the non-convex constraint (14c) can be transformed into a convex one as

$$\frac{1}{N}\sum_{n=1}^{N}\left(\log_2(p_u\rho_0+(\sigma^2+Ph_{mi})(H^2+S_{mi}[n]))-\widehat{R}_{mi}^{ub}[n]\right)\geq\gamma, \tag{21}$$

where

$$\widehat{R}_{mi}^{ub}[n]=E_{mi}^r[n]\left(\|\mathbf{q}[n]-\mathbf{W}_k\|^2-\|\mathbf{q}^r[n]-\mathbf{W}_k\|^2\right)+F_{mi}^r[n], \tag{22}$$

$$E_{mi}^r[n]=\frac{\sigma^2\log_2(e)}{p_u\rho_0+\sigma^2\left(H^2+\|\mathbf{q}^r[n]-\mathbf{W}_{mi}\|^2\right)}\geq 0, \tag{23}$$

$$F_{mi}^r[n]=\log_2\left(p_u\rho_0+\sigma^2\left(H^2+\|\mathbf{q}^r[n]-\mathbf{W}_{mi}\|^2\right)\right). \tag{24}$$

In addition, $S_{mi}[n]$ should satisfy

$$S_{mi}[n]\leq\|\mathbf{q}^r[n]-\mathbf{W}_{mi}\|^2+2\left(\mathbf{q}^r[n]-\mathbf{W}_{mi}\right)^T(\mathbf{q}[n]-\mathbf{q}^r[n]). \tag{25}$$

Proof: First, we rewrite the left-hand-side of the constraint (14c) as a difference of two functions

$$\begin{aligned}&\log_2\left(1+\frac{Ph_{mi}}{\frac{p_u\rho_0}{H^2+\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2}+\sigma^2}\right)\\&=\log_2\left(p_u\rho_0+\left(\sigma^2+Ph_{mi}\right)\left(H^2+\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2\right)\right)-\widehat{R}_{mi}[n],\end{aligned} \tag{26}$$

where

$$\widehat{R}_{mi}[n]=\log_2\left(p_u\rho_0+\sigma^2\left(H^2+\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2\right)\right). \tag{27}$$

It is easy to observe that $\widehat{R}_{mi}[n]$ is concave with respect to $\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2$, although it is not convex with respect to $\mathbf{q}[n]$. Recall that the first-order Taylor series expansion of a concave function is its upper bound. Thus, with given UAV trajectory $\mathbf{Q}^r$ in the rth iteration, we have the following equation in the $(r+1)$th iteration.

$$\begin{aligned}\widehat{R}_{mi}[n] &\le E^r_{mi}[n]\left(\|\mathbf{q}[n]-\mathbf{W}_k\|^2-\|\mathbf{q}^r[n]-\mathbf{W}_k\|^2\right)+F^r_{mi}[n]\\ &=\widehat{R}^{ub}_{mi}[n],\end{aligned} \tag{28}$$

where $E^r_{mi}[n]$ and $F^r_{mi}[n]$ are constants expressed as (23) and (24). Obviously, $\widehat{R}^{ub}_{mi}[n]$ is convex with respect to $\mathbf{q}[n]$.

On the other hand, the first term (i.e., minuend) in (26) is concave with respect to $\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2$. Thus, we can introduce slack variables $\mathbf{S}=\{S_{mi}[n]\le\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2, \forall i\in\mathcal{I}_m, \forall m\in\{1,2,3\}, \forall n\}$ to approximatively rewrite the constrain (14c) as (21) for all $i\in\mathcal{I}_m, m\in\{1,2,3\}$. Then, the minuend function in (21) is concave with respect to $S_{mi}[n]$. Thus, the constrain (21) is jointly convex with respect to $\mathbf{q}[n]$ and $S_{mi}[n]$.

Nevertheless, the introduction of relaxation variables $S_{mi}[n]$ adds a new constraint to the optimization problem in (14) as

$$S_{mi}[n]\le\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2, \forall i\in\mathcal{I}_m, \forall m\in\{1,2,3\}, \forall n. \tag{29}$$

Similarly, since $\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2$ is convex with respect to $\mathbf{q}[n]$, its lower bound can be obtained by using the first-order Taylor series expansion, i.e., with given UAV trajectory $\mathbf{Q}^r$, in the $(r+1)$th iteration, we have

$$\begin{aligned}&\|\mathbf{q}[n]-\mathbf{W}_{mi}\|^2\\ &\ge\|\mathbf{q}^r[n]-\mathbf{W}_{mi}\|^2+2\left(\mathbf{q}^r[n]-\mathbf{W}_{mi}\right)^T\left(\mathbf{q}[n]-\mathbf{q}^r[n]\right).\end{aligned} \tag{30}$$

Then, we can obtain (25), which is convex quadratic. ■

Based on Lemma 1 and Lemma 2, we can transform (14) into a convex problem as in Theorem 1.

Theorem 1: With given UAV trajectory $\mathbf{Q}^r$ obtained in the rth iteration, (14) can be approximated as (31) in the $(r+1)$th iteration, which is convex.

$$\max_{\mathbf{Q},\mathbf{S}} \sum_{k\in\mathcal{K}}\left(\frac{1}{N}\sum_{n=1}^{N}\widehat{\alpha}_k[n]\widehat{R}^{[k]}_{ulb}[n]\right) \tag{31a}$$

$$s.t.\ (15),(21),(25),(1),(2). \tag{31b}$$

Proof: Based on Lemma 1, the lower bound of R^{sum}_u can be obtained as

$$R^{sum}_u\ge\sum_{k\in\mathcal{K}}\left(\frac{1}{N}\sum_{n=1}^{N}\widehat{\alpha}_k[n]\widehat{R}^{[k]}_{ulb}[n]\right). \tag{32}$$

Since $\widehat{R}^{[k]}_{ulb}[n]$ is concave with respect to $\mathbf{q}[n]$, the right-hand-side of inequation (32) is concave with respect to $\mathbf{q}[n]$. Thus, the maximization of the lower bound of R^{sum}_u is convex. In addition, the constraints in (31b) are convex or linear according to Lemma 1 and Lemma 2. Therefore, (31) is a convex optimization problem, which can be solved by using classical optimization methods. ■

C. Iterative Algorithm

Based on the results above, we can divide the entire optimization variables in problem (11) into two steps, i.e., $\mathbf{A}$ and $\mathbf{Q}$, which can be optimized by solving the problem (13) and (31) alternately. The whole iterative algorithm can be summarized as Algorithm 1, which is guaranteed to converge quickly with a sub-optimal solution obtained. The computational complexity of (11) can be reduced significantly by Algorithm 1 due to the convexity of (13) and (31).

Algorithm 1 Iterative algorithm for problem (11)

1: Initialize $\mathbf{Q}^0$, let $r=0$.
2: **repeat**
3: Solve convex problem (13) with given $\mathbf{Q}^r$, and denote the solution as $\mathbf{A}^{r+1}$.
4: Solve convex problem (31) with given $\mathbf{A}^{r+1}$, and denote the solution as $\mathbf{Q}^{r+1}$.
5: Update $r=r+1$.
6: **until** The increase of the objective function is below a predefined threshold $\epsilon>0$.

After Algorithm 1, the variables $\widehat{\alpha}_k[n]$ can be discretized into binary ones as

$$\alpha_k[n]=\begin{cases}1, & \widehat{\alpha}_k[n]\ge 0.5,\\ 0, & \widehat{\alpha}_k[n]<0.5.\end{cases} \tag{33}$$

Remark: In the proposed UAV trajectory scheme, the UAV should fly close to its served users to improve their performance. At the same time, the UAV should stay away from the BS served users, to avoid generating interference to them. Therefore, the UAV trajectory should be traded off to optimize the QoS of edge users, which will be shown through simulation in Section IV.

IV. Simulation Results and Discussions

In this section, simulation results are presented to demonstrate the performance of the proposed trajectory optimization scheme. In the simulation, we set $r_c=1$ km, $r_b=500$ m, $H=100$, $\rho_0=-60$ dB, $\alpha_0=-40$ dB, $\sigma^2=-110$ dBm, $V=50$ m/s, $T=120$ s, $P=p_u=0.1$ W, $\gamma=1.5$ bit/s/Hz, and $\eta=0.5$ bit/s/Hz. Two cases are considered for different locations of the 2nd user served by the 2nd BS. Compared to Case I, the user location $\mathbf{W}_{22}$ is changed to be very close to the edge area in Case II. In this paper, the UAV trajectory is optimized to maximize the sum rate (MSR) of edge users with additional constraints, and the simulations results of the two cases are shown in Fig. 2. The average sum rate and transmission rate of each edge user are also compared in the first two rows of Table I for these two cases, in bit/s/Hz. On the other hand, we can also maximize the minimum average rate (MMR) of all the edge users with the same constraints in (11), which can be solved similarly to our proposed solution in Section III. The corresponding simulation results of the MMR scheme are shown in Fig. 3 and last two rows of Table I.

From the results, we can see that the average sum rate of edge users in the MSR scheme can be maximized by

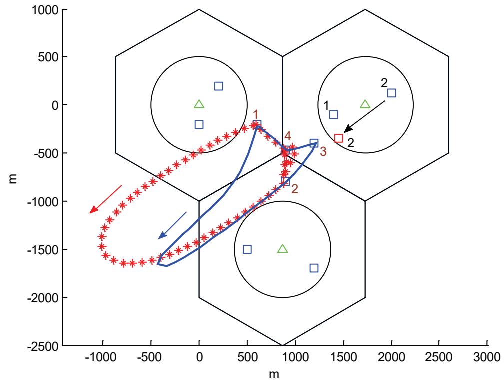

Fig. 2. UAV trajectory optimization in the MSR scheme. Trajectory of Case I is blue, while Case II is red. BSs are marked by green △. Users are marked by blue □, and the 2nd user of the 2nd BS in Case II is marked by red □.

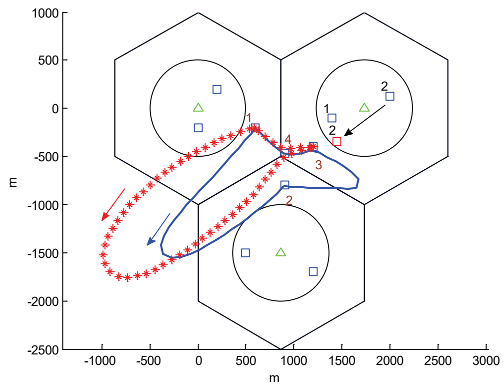

Fig. 3. UAV trajectory optimization in the MMR scheme. The curves and points are marked similarly to those in Fig. 2.

optimizing the UAV trajectory with the rate requirements of all the users satisfied. However, for some edge users, e.g., the 4th user, their average transmission rate is as low as the rate threshold (0.5 bit/s/Hz). One the other hand, for the MMR scheme, the minimum transmission rate of the edge users can be optimized, and thus, the fairness between users can be guaranteed. Nevertheless, the sum rate of the MMR scheme is sacrificed, which is much lower than that of the MSR scheme. In addition, we can see that when the 2nd user served by the 2nd BS moves to the edge area in Case II, the optimized trajectory will move far away from this user, to avoid strong interference to it and guarantee its QoS. Correspondingly, the performance of both the schemes in Case I is better than that in Case II, due to the fact that the interference will become stronger when the users served by UAV and BSs become closer, no matter which optimization is taken.

V. Conclusions

In this paper, the UAV trajectory optimization for data offloading in the edge area of multiple cells has been researched. In the proposed scheme, three adjacent cells were considered, and the trajectory was optimized to maximize the sum rate of edge users by avoiding the interference between BSs and UAV, with the rate requirements of all the mobile users satisfied. To solve this non-convex problem, it was first transformed into two convex subproblems, and then, an effective algorithm was proposed to calculate the solutions alternately. Simulation results were presented to show the effectiveness of the proposed scheme in UAV trajectory design. In our future work, we will continue to focus on the multi-UAV scenario of trajectory optimization for data offloading.

TABLE I
Rate Comparison of Edge Users in MSR and MMR Schemes.

Case	Sum rate	User 1	User 2	User 3	User 4
MSR-Case I	4.5494	0.5000	2.3587	1.1849	0.5059
MSR-Case II	2.9971	0.5000	1.4970	0.5000	0.5000
MMR-Case I	3.4772	0.8693	0.8693	0.8693	0.8693
MMR-Case II	2.9532	0.7383	0.7383	0.7383	0.7383

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