Joint User Scheduling and UAV Trajectory Optimization for Full-Duplex UAV Relaying

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***Abstract*—Based on the advantages of small size, light weight, as well as flexible deployment and recycling, unmanned aerial vehicle (UAV) has been more and more widely used in military and civilian. As flying relays, UAVs can quickly set up relay communication links for different missions, to enhance the receiving signal power, increase the system capacity, and expand the communication coverage. In this paper, we investigate full-duplex (FD) UAV relaying for multiple source-destination pairs. To fully exploit the flying flexibility of the UAV in serving multiple source-destination pairs, we propose a scheduling protocol that exploits time division multiple access (TDMA) to serve different source-destination pairs in turns when flying along an optimized trajectory. Then, we further formulate a joint optimization problem of the TDMA-based user scheduling and the dynamic UAV trajectory to maximize the system throughput. The formulated problem is non-convex which makes it difficult to solve directly, hence we propose an iterative algorithm to obtain an approximate optimal solution based on block coordinate descent and successive convex optimization techniques. Simulation results demonstrate that our proposed TDMA-based protocol outperforms the OFDMA-based ones with fixed UAV position/trajectory when the UAV helps relay information for multiple source-destination pairs.**

***Index Terms*—UAV communication, full-duplex, throughput maximization, trajectory design, multiple source-destination pairs, resource allocation.**

I. Introduction

Unmanned aerial vehicles (UAVs) originate in the military field and are used for reconnaissance, surveillance, surveying and mapping, air strikes and other military purposes. In recent years, with the advancement of key technologies such as flight control, navigation, and communications as well as the reduction of costs, UAVs have also been widely adopted in civil domain, including freight, engineering construction, and communication networks [1]. Based on the advantages of relay transmission compared with traditional single-hop communications, such as significantly enhancing system coverage, markedly reducing information transmission loss, and effectively improving communication reliability, the combination of relay transmission technology and UAVs is expected to become an attractive solution to improve the capability of existing wireless communications [2].

A lot of work has been accumulated in the field of UAV relaying communications. Throughput maximization algorithms that jointly optimizes the UAV trajectory and the source/relay transmit power was designed in [3]. Also considering the joint optimization of the transmit power and the UAV trajectory, authors in [4] investigated the minimization of interruption probability, when the UAV acts as a relay node to exchange information between a mobile device and a base station (BS). A scenario where a full-duplex (FD) UAV relay shares spectrums with ground device-to-device pairs was considered in [5], which will cause mutual interference. Aiming at the reliability, work in [6] solved the optimal height of the UAV relay aiming at total power loss, total interruption probability, and total error rate, respectively. To minimize the outage probability, work in [7] derived the optimal coordinate and optimal beam pattern of the UAV relay, and analyzed the influence of the intensity of UAV's orientation fluctuations as well as the position and height of obstacles. A radio resource optimization method for relay-based UAV was proposed in [8].

Most existing works focused on the single user pair scenario when investigating UAV relaying issues, however, in practical applications there are often multiple source-destination pairs requesting for relaying services at the same time [9]. Some recent studies have taken such a scenario into consideration. In [10], to maximize the system throughput, one static rotary-wing UAV working on frequency division multiplexing (FDM) was investigated as a relay to assist multiple ground user pairs, where the location of UAV, transmission rate, transmit power, and bandwidth were designed jointly. Work in [11] extended the static UAV in [10] to fly along a constant trajectory such as a circle with certain speed and altitude. Also exploiting FDM, authors in [11] designed power optimization based on fixed trajectories with the goal of maximizing throughput. However, these works do not fully exploit the flexibility of the UAV relays when they serve multiple source-destination pairs by taking the dynamic UAV trajectory optimization into consideration.

Inspired by the above discussions, in this paper, we for the first time investigate FD-based UAV relaying for multiple source-destination pairs. Although FD technique has the ability to enhance the spectral efficiency of the relaying system, it poses a new challenge for the application in UAV relaying especially in the dynamic trajectory scheduling of UAVs. Different from current works on UAV relaying for multiple source-destination pairs, we take the dynamic UAV trajectory scheduling into consideration, and employ time division multiple access (TDMA) as the multiple access control (MAC) design to fully exploit the benefits of the flexibility of the UAV in serving multiple user pairs in different locations. To achieve system throughput maximization, we formulate a joint optimization problem of the TDMA-based user scheduling and the dynamic UAV trajectory, and further adopt an iterative algorithm to work out it efficiently. Simulation results verify the efficiency of our design in significantly improving the network throughput in such a UAV relaying scenario with multiple source-destination pairs, compared with the orthogonal frequency division multiple access (OFDMA) based fixed UAV position/trajectory protocols.

The rest of this paper is organized as follows. In Section II, the system model of FD-based UAV relaying network and the problem formulation are introduced. Section III provides an iterative algorithm to optimize user scheduling and UAV trajectory jointly. Section IV demonstrates the numerical results. Finally, Section VI concludes this paper.

II. System Model and Problem Formulation

A. System Model

In this section, we consider a FD UAV relaying scenario with multiple ground source-destination pairs and one UAV behaving as an intermediate relay. As illustrated in Fig. 1, one UAV is deployed to relay data packets from M source nodes $S_1, S_2, \ldots, S_M$ to M corresponding destination nodes $D_1, D_2, \ldots, D_M$. The source and destination nodes are all located on the ground. Each source-destination pair is assumed to be incapable of direct communications.The intermediate UAV relay works in the FD mode.We assume that one relaying task duration of the UAV is T, during which the UAV takes off from a specified initial location, flies along an optimized trajectory for information relaying, and then lands at the final location. TDMA is adopted so that the UAV serves different source-destination pairs in different time slots.

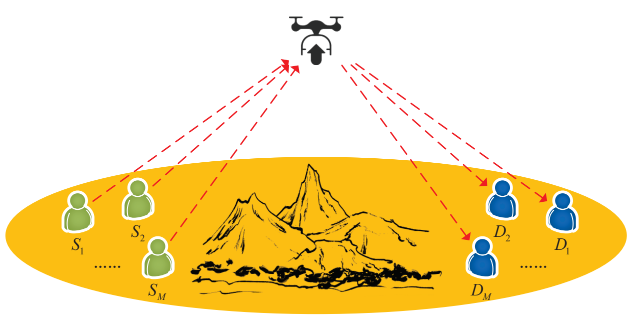

Fig. 1. A FD UAV relaying scenario with multiple ground source-destination pairs.

In this system, we suppose the source and destination nodes S_m and D_m, $m = 1, \ldots, M$, are located at $\mathbf{C}_{S_m} = [\mathbf{l}_{S_m}^T, 0]^T$ and $\mathbf{C}_{D_m} = [\mathbf{l}_{D_m}^T, 0]^T$, respectively, where $\mathbf{l}_{S_m} = [x_{S_m}, y_{S_m}]^T$ and $\mathbf{l}_{D_m} = [x_{D_m}, y_{D_m}]^T$ are the horizontal coordinates. The exact coordinates of the nodes can be obtained in advance by localization technologies such as global positioning system (GPS). The flying altitude of the UAV is assumed to be a fixed value H, which in practice corresponds to the lowest elevation needed to avoid all terrains or buildings in a specific environment [3]. For simplicity, the take-off and landing phases of the UAV are ignored, and only the horizontal flight during T is concerned. Hence, the UAV's coordinate at time t is $\mathbf{C} = [\mathbf{l}(t)^T, H]^T$, $0 \leq t \leq T$, where $\mathbf{l}(t) = [x(t), y(t)]^T$ denotes the UAV's horizontal coordinate at time t.

The time period T is divided into K equal time slots, $T = K d_t$, with the size of one time slot d_t is set to be sufficiently small that the position of the UAV in d_t can be regarded as approximately constant. Therefore, the trajectory $\mathbf{l}(t)$ during whole period T can be represented by a K-length sequence $\mathbf{l}[k] = [x[k], y[k]]^T$, $k \in \{1, \ldots, K\}$, where $(x[k], y[k])$ denotes the UAV's horizontal coordinate at time slot k. The UAV's maximum flying speed is set as v_{max}, and then the maximum flying distance of the UAV in one time slot is $D_{max} = v_{max} d_t$. The initial and final horizontal coordinateS of the UAV are denoted by $\mathbf{l}_0 = [x_0, y_0]^T$ and $\mathbf{l}_F = [x_F, y_F]^T$, respectively. Then, the mobility of the UAV's constraints can be given as

$$\begin{aligned} \|\mathbf{l}[1] - \mathbf{l}_0\| &\leq D_{max}, \\ \|\mathbf{l}_F - \mathbf{l}[K]\| &\leq D_{max}, \\ \|\mathbf{l}[k] - \mathbf{l}[k-1]\| &\leq D_{max}, k = 2, \ldots, K, \end{aligned} \tag{1}$$

where $\|\cdot\|$ denotes the Euclidean norm.

In addition, the UAV is assumed to be provided with a data buffer that is large enough to satisfy the required data storage capacity for DF relaying. The air-to-ground (A2G) channels are dominated by line-of-sight (LoS) links, and the Doppler effect caused by the UAV's mobility can be completely compensated. Therefore, at time slot k, the channel gain from source node S_m to the UAV relay follows the free-space path loss model as

$$h_{S_m}[k] = \beta_0 d_{S_m}^{-2}[k] = \frac{\beta_0}{H^2 + \|\mathbf{l}[k] - \mathbf{l}_{S_m}\|^2}, \tag{2}$$

where β_0 denotes the channel gain at the reference distance $d_0 = 1$ m. And $d_{S_m}[k] = \sqrt{H^2 + \|\mathbf{l}[k] - \mathbf{l}_{S_m}\|^2}$ is the distance between S_m and the UAV relay at time slot k. Similarly, the channel from the UAV relay to destination node D_m at time slot k is expressed as

$$h_{D_m}[k] = \beta_0 d_{D_m}^{-2}[k] = \frac{\beta_0}{H^2 + \|\mathbf{l}_{D_m} - \mathbf{l}[k]\|^2}, \tag{3}$$

where $d_{D_m}[k] = \sqrt{H^2 + \|\mathbf{l}[k] - \mathbf{l}_{D_m}\|^2}$ is the distance between D_m and the UAV relay at time slot k.

We use a binary variable $\alpha_m[k]$ to represent the time slot allocation in the TDMA-based UAV relaying transmission.

When the UAV serves source-destination pairs m at time slot k, $\alpha_m[k]=1$; otherwise, $\alpha_m[k]=0$. Due to TDMA, at most one source-destination pair can be served by the UAV relay at a certain time slot, and thus the time slot allocation is subject to

$$\sum_{m=1}^{M}\alpha_m[k]\leq 1,\forall k, \tag{4}$$
$$\alpha_m[k]\in\{0,1\},\forall m,k. \tag{5}$$

Considering the self-interference of the FD UAV relay, the transmission rate from source node S_m to the UAV relay at time slot k is

$$\begin{aligned} G_{S_m}[k] &= B\log_2\left(1+\frac{P_S h_{S_m}[k]}{P/\kappa+\sigma^2}\right)\\ &= B\log_2\left(1+\frac{P_S\beta_0}{(H^2+\|\mathbf{l}[k]-\mathbf{l}_{S_m}\|^2)(P/\kappa+\sigma^2)}\right), \end{aligned} \tag{6}$$

where P_S and P are the transmit power of source nodes and UAV, B is the channel bandwidth, σ^2 is the power of additive white Gaussian noise (AWGN) at the destination nodes, and κ is the self-interference cancellation coefficient [12], $0\leq\kappa\leq 1$. The transmission rate from the UAV relay to destination node D_m at time slot k is

$$\begin{aligned} G_{D_m}[k] &= B\log_2\left(1+\frac{P h_{D_m}[k]}{\sigma^2}\right)\\ &= B\log_2\left(1+\frac{P\beta_0}{(H^2+\|\mathbf{l}[k]-\mathbf{l}_{D_m}\|^2)\sigma^2}\right). \end{aligned} \tag{7}$$

Then, the transmission rate of source-destination pair m can be calculated as $G_m[k]=\min(G_{S_m}[k],G_{D_m}[k])$. Therefore, the average transmission rate of source-destination pair m over K time slots can be given as

$$G_m=\frac{1}{K}\sum_{k=1}^{K}\alpha_m[k]G_m[k]. \tag{8}$$

B. Problem Formulation

Our objective average rate among all ground source-destination pairs is constrained by mobility constraints in (1), user scheduling constraints (4) and (5), where there are two variables: UAV's trajectories $\mathbf{l}\triangleq\{\mathbf{l}[1],\dots,\mathbf{l}[K]\}$ and user scheduling $\boldsymbol{\alpha}=\{\boldsymbol{\alpha}_1,\dots,\boldsymbol{\alpha}_M\}$, where $\boldsymbol{\alpha}_m=[\alpha_m[1],\dots,\alpha_m[K]]^T$. Define $\mu(\mathbf{l},\{\boldsymbol{\alpha}_m\})=\min\{G_1,\dots,G_M\}$ as a function of $\mathbf{l}$ and $\{\boldsymbol{\alpha}_m\}$. The optimization problem can be formulated as

$$\text{(P1):}\ \max_{\mathbf{l},\{\boldsymbol{\alpha}_m\}}\ \mu \tag{9a}$$
$$\text{s.t.}\ \frac{1}{K}\sum_{k=1}^{K}\alpha_m[k]G_m[k]\geq\mu,\forall m, \tag{9b}$$
$$\sum_{m=1}^{M}\alpha_m[k]\leq 1,\forall k, \tag{9c}$$
$$\alpha_m[k]\in\{0,1\},\forall m,k. \tag{9d}$$
$$\|\mathbf{l}[1]-\mathbf{l}_0\|\leq D_{max}, \tag{9e}$$
$$\|\mathbf{l}_F-\mathbf{l}[K]\|\leq D_{max}, \tag{9f}$$
$$\|\mathbf{l}[k]-\mathbf{l}[k-1]\|\leq D_{max}, k=2,\dots,K, \tag{9g}$$

which is difficult to solve directly. Firstly, the user scheduling variables $\boldsymbol{\alpha}$ are binary, which makes (9b)-(9d) become integer constraints. Second, $G_m[n]$ in constraints (9b) is non-convex. Hence, in the following section, we provide an effective algorithm for the above optimization problem (P1) through iteratively optimizing the user scheduling and trajectories.

III. Joint Optimization of User Scheduling and Trajectory

To avoid the integer constraint problem, we relax the user scheduling variables $\boldsymbol{\alpha}$ in (9d) to be continuous, which turns the problem (9) into the following problem

$$\text{(P2):}\ \max_{\mathbf{l},\{\boldsymbol{\alpha}_m\}}\ \mu \tag{10a}$$
$$\text{s.t.}\ 0\leq\alpha_m[k]\leq 1,\forall m,k, \tag{10b}$$
$$\text{(9b), (9c), (9e), (9f), (9g).} \tag{10c}$$

This relaxation makes the optimal solution of the problem (P2) to be an upper bound for that of the problem (P1). Then, block coordinate descent (BCD) can be used to solve the multivariable optimization problem (P2), which can obtain the optimal solution by performing optimization in one direction at a time.

A. User Scheduling Optimization

With fixed trajectory $\mathbf{l}$, the subproblem of user scheduling can be expressed as

$$\text{(P3):}\ \max_{\{\boldsymbol{\alpha}_m\}}\ \mu, \tag{11a}$$
$$\text{s.t.,}\ \frac{1}{K}\sum_{n=1}^{K}\alpha_m[k]G_m[k]\geq\mu,\forall m, \tag{11b}$$
$$\sum_{m=1}^{M}\alpha_m[k]\leq 1,\forall k, \tag{11c}$$
$$0\leq\alpha_m[k]\leq 1,\forall m,k. \tag{11d}$$

It can be found that problem (P3) is already a linear programming that can be easily solved by existing convex optimization toolbox such as CVX.

B. Trajectory Optimization

With optimized user scheduling, we further study the UAV trajectory optimization subproblem. Let $\gamma_S[k] \triangleq \frac{P_S\beta_0}{P/\kappa+\sigma^2}$, $\gamma_D[k] \triangleq \frac{P\beta_0}{\sigma^2}$. Then, we define

$$\begin{aligned} R_{S_m}(\mathbf{l}[k]) &\triangleq \log_2\left(1+\frac{\gamma_S[k]}{H^2+\|\mathbf{l}[k]-\mathbf{l}_{S_m}\|^2}\right), \\ R_{D_m}(\mathbf{l}[k]) &\triangleq \log_2\left(1+\frac{\gamma_D[k]}{H^2+\left\|\mathbf{l}_[k]-\mathbf{l}_{D_m}\right\|^2}\right). \end{aligned} \tag{12}$$

Then, with optimized user scheduling decision $\{\boldsymbol{\alpha}_m\}$, the optimization subproblem of the UAV's trajectory can be expressed as

$$\text{(P4):} \max_{\mathbf{l}} \mu \tag{13a}$$

$$\text{s.t. } \frac{B}{K}\sum_{k=1}^{K}\alpha_m[k]min\left(R_{S_m}(\mathbf{l}[k]), R_{D_m}(\mathbf{l}[k])\right) \geq \mu, \forall m, \tag{13b}$$

$$\|\mathbf{l}[1]-\mathbf{l}_0\| \leq D_{max}, \tag{13c}$$

$$\|\mathbf{l}_F-\mathbf{l}[K]\| \leq D_{max}, \tag{13d}$$

$$\|\mathbf{l}[k]-\mathbf{l}[k-1]\| \leq D_{max}, k=2,\ldots,K. \tag{13e}$$

But the constraints (13b) are non-convex concerning $\{\mathbf{l}[k]\}$, which makes (P4) difficult to work out. And thus we design an approximate optimal solution of this subproblem by iteratively using successive convex optimization methods. Let $\{\mathbf{l}^z[k]\}$ represent the trajectories calculated in the lth iteration. It can be seen that $R_{S_m}(\mathbf{l}[k])$ is not concave concerning $\mathbf{l}[k]$, but it is convex concerning $\|\mathbf{l}[k]-\mathbf{l}_{S_m}\|^2$. Since the convex function has the property that the first-order Taylor expansions is its global lower bound [13], we use the first-order Taylor expansion of of $R_{S_m}(\mathbf{l}[k])$ at $\|\mathbf{l}[k]-\mathbf{l}_{S_m}\|^2$ as its lower-bound, denoted as $R^{lb}_{S_m}(\mathbf{l}[k])$

$$\begin{aligned} &R_{S_m}(\mathbf{l}[k]) \\ &= \log_2\left(1+\frac{\gamma_S[k]}{H^2+\|\mathbf{l}[k]-\mathbf{l}_{S_m}\|^2}\right) \\ &\geq R^{lb}_{S_m}(\mathbf{l}[k]) \\ &\triangleq \alpha^z_{S_m}[k]-\beta^z_{S_m}[k](\|\mathbf{l}[k]-\mathbf{l}_{S_m}\|^2-\|\mathbf{l}^z[k]-\mathbf{l}_{S_m}\|^2), \end{aligned} \tag{14}$$

where

$$\alpha^z_{S_m}[k] = \log_2\left(1+\frac{\gamma_S[k]}{H^2+\|\mathbf{l}^z[k]-\mathbf{l}_{S_m}\|^2}\right), \tag{15}$$

$$\begin{aligned} &\beta^z_{S_m}[k] \\ &= \frac{(\log_2 e)\gamma_S[k]}{(H^2+\gamma_S[k]+\|\mathbf{l}^z[k]-\mathbf{l}_{S_m}\|^2)(H^2+\|\mathbf{l}^z[k]-\mathbf{l}_{S_m}\|^2)}. \end{aligned} \tag{16}$$

Note that $R^{lb}_{S_m}(\mathbf{l}[k])$ is concave concerning $\mathbf{l}[k]$. Similarly, we get the lower-bound of $R_{D_m}(\mathbf{l}[k])$, denoted as $R^{lb}_{D_m}(\mathbf{l}[k])$, and then we have

$$\begin{aligned} &R_{D_m}(\mathbf{l}[k]) \\ &= \log_2\left(1+\frac{\gamma_D[k]}{H^2+\|\mathbf{l}[k]-\mathbf{l}_{D_m}\|^2}\right) \\ &\geq R^{lb}_{D_m}(\mathbf{l}[k]) \\ &\triangleq \alpha^z_{D_m}[k]-\beta^z_{D_m}[k](\|\mathbf{l}[k]-\mathbf{l}_{D_m}\|^2-\|\mathbf{l}^z[k]-\mathbf{l}_{D_m}\|^2), \end{aligned} \tag{17}$$

where

$$\alpha^z_{D_m}[k] = \log_2\left(1+\frac{\gamma_D[k]}{H^2+\|\mathbf{l}^z[k]-\mathbf{l}_{D_m}\|^2}\right), \tag{18}$$

$$\begin{aligned} &\beta^z_{D_m}[k] \\ &= \frac{(\log_2 e)\gamma_D[k]}{(H^2+\gamma_D[k]+\|\mathbf{l}^z[k]-\mathbf{l}_{D_m}\|^2)(H^2+\|\mathbf{l}^z[k]-\mathbf{l}_{D_m}\|^2)}. \end{aligned} \tag{19}$$

We have that $R^{lb}_{D_m}(\mathbf{l}[k])$ is also concave concerning $\mathbf{l}[k]$.

By replacing the terms $R_{S_m}(\mathbf{l}[k])$ and $R_{D_m}(\mathbf{l}[k])$ in (13b) with the lower bounds given in (14) and (17), problem (P4) can be approximately reformulated as

$$\text{(P5):} \max_{\mathbf{l}} \mu \tag{20a}$$

$$\text{s.t. } \frac{B}{K}\sum_{k=1}^{K}\alpha_m[k]min\left(R^{lb}_{S_m}(\mathbf{l}[n]), R^{lb}_{D_m}(\mathbf{l}[k])\right) \geq \mu, \forall m, \tag{20b}$$

$$\|\mathbf{l}[1]-\mathbf{l}_0\| \leq D_{max}, \tag{20c}$$

$$\|\mathbf{l}_F-\mathbf{l}[K]\| \leq D_{max}, \tag{20d}$$

$$\|\mathbf{l}[k]-\mathbf{l}[k-1]\| \leq D_{max}, k=2,\ldots,K, \tag{20e}$$

which becomes convex optimization problem.

C. Joint Optimization Algorithm

Based on the above two parts, we provide an algorithm to optimize user scheduling and UAV trajectory jointly, as shown in Algorithm 1.

Algorithm 1 Joint Optimization Algorithm of User Scheduling, Power, and UAV Trajectory

1: Initialize a feasible trajectory $\mathbf{l}^0$. Let $z=0$
2: **repeat**
3: Find the optimal solution $\{\boldsymbol{\alpha}^z_m\}$ of problem (P3) with given $\mathbf{l}^z$.
4: Find the optimal solution $\mathbf{l}^{z+1}$ of problem (P5) with given $\{\boldsymbol{\alpha}^z_m\}$.
5: Update $z=z+1$.
6: **until** The improvement of the end-to-end throughput is smaller than a given threshold $\epsilon > 0$.

Specifically, we iteratively solve subproblems of user scheduling and UAV trajectory optimization to find a sub-optimal solution of problem (P2). As shown in the above two subsections, the optimal value of (P2) with the solutions obtained by iteratively solving problems (P3) and (P5) are non-decreasing. Therefore, the proposed algorithm is guaranteed to converge.

It is worth noting that Algorithm 1 actually solves the scaling problem (P2), where the variables $\{\boldsymbol{\alpha}_m\}$ are continuous variables rather than desired integer variables. Therefore, if all the variables $\{\boldsymbol{\alpha}_m\}$ calculated by Algorithm 1 are binary, problem (10) is a tight relaxation of the problem (9) and the obtained result is a local optimal user scheduling solution of problem (9). Otherwise some time slot needs to be further divided into $\tau[k]$ sub-time slots, i.e., $N'[k] = \tau[k]K, \tau[k] \geq 1$. Now, the number of sub-time slots divided into source-destination pair m in time slot k can be expressed as $N_m[k] = \tau[k]\alpha_m[k]$. As $\tau[k]$ increases, obviously we can always find a $\tau[k]$ large enough that all $N_m[k]$ are integers. At this moment, the UAV becomes to serve at most one user pair at each sub-time slot. Then, the user scheduling result becomes binary and is the locally optimal solution of the problem (9).

IV. Simulation Results

In this section, numerical examples are demonstrated to show the effectiveness of our proposed algorithm. We consider a FD-based UAV relaying system with $M = 5$ source-destination pairs that are stochastically distributed over a $1.4 \times 1.4\ \mathrm{km}^2$ geographic area. The source-destination pairs are assumed to be distributed in a random distribution as shown in Fig. 2. The altitude of the UAV is fixed to $H = 100$ m, and the initial and final horizontal positions of the UAV are set to be the same, that is, $l_0 = l_F = [0, 700]^T$ m, which is a reasonable assumption due to the fact that the UAV takes off and lands from the same console in most cases. The length of one time slot is set as $d_t = 2$ s, and the maximum speed of UAVs is assumed to be $v_{max} = 30$ m/s. Furthermore, we set $P = P_S = P_o$. The reference channel power at $d_0 = 1$ m is assumed to be $\beta_0 = -50$ dB. The AWGN power and channel bandwidth are set as $\sigma^2 = -110$ dBm and $B = 10$ Mhz. And the self-interference cancellation coefficient of the UAV is set as $\kappa = 100$ dB.

A. UAV Trajectory with Different Time Period T

Fig. 2 shows the optimized UAV trajectories for different horizontal task duration T. The transmission power is set as $P_o = 0.1$ W.

Limited by flight speed, it takes at least 90 s for the UAV to arrive the best static relay location between S_5 and D_5. When the task duration is set as $T_1 = 70$ s, it is not long enough for the UAV to reach near the best static relay location between S_5 and D_5. As shown in Fig. 2, the trajectory trend of the UAV relay is consistent with the geographical distribution trend of source-destination pairs. This shows that our scheme enables

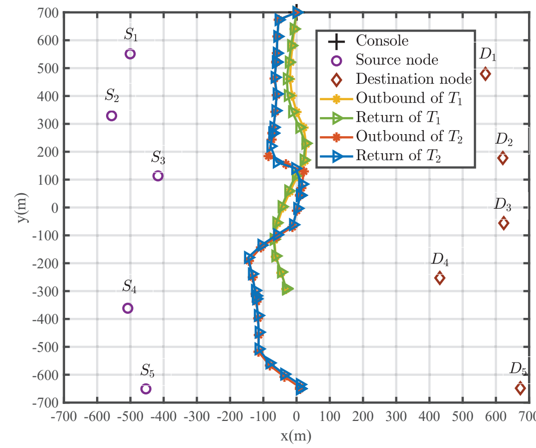

Fig. 2. UAV Trajectories with Different Time Period T.

the UAV to choose the best flight trajectory according to different channel conditions when serving the specific source-destination pair. We can also observe that the outbound and return trajectories of the UAV are completely coincident. This is because these two trajectories have the same constraints except for different directions, so they are both consistent with the geographical distribution of source-destination pairs. When the flight duration is set as $T_2 = 300$ s, it is long enough for the UAV to reach near the best static relay location between S_5 and D_5. Now, the flight trajectory trend of the UAV is also consistent with the geographical distribution trend of source-destination pairs. The difference is that, because the flight duration is long enough, the UAV can hover over the best transmission location for the current assigned source-destination pair to achieve a better transmission rate before flying to the next source-destination pair's best transmission location. The outbound and return trajectories of the UAV for $T_2 = 300$ s are roughly coincident, which is also due to the fact that the two trajectories have the same constraints except for different directions, so they are both consistent with the geographical distribution of source-destination pairs.

B. TDMA-Based User Scheduling versus OFDMA-Based User Scheduling

Fig. 3 compares the average transmission rate between our proposed TDMA-based user scheduling and the traditional OFDMA-based user scheduling. For the OFDMA-based user scheduling, the UAV is assumed to serve multiple source-destination pairs simultaneously, that is, it is assumed that the frequency band allocated to each source-destination pair is $\frac{B}{M}$ and the transmitting power of UAV is constant and equally distributed to each source-destination pair, i.e., $\hat{P} = \frac{P_{max}}{M}$. Since all source-destination pairs are served equally, the UAV's trajectory of OFDMA transmission scheme denoted by $\{\hat{\mathbf{l}}[k]\}$ is simply assumed to be line-segment trajectory. The UAV in the OFDMA scheme flies from the console to the center of all source-destination pairs at the fastest speed, then stays stationary, and finally flies back to the console according to the maximum speed.

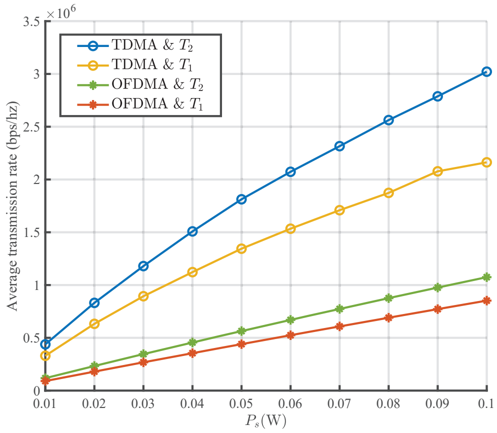

Fig. 3. TDMA-Based User Scheduling versus OFDMA-Based User Scheduling.

From Fig. 3, we get the following important observations. First, as expected, the average transmission rate of all the schemes increases as the transmit power P_o increases. Second, for the TDMA-based user scheduling, when the power is fixed, the average transmission rate corresponding to $T_2 = 300$ s is significantly higher than that of $T_1 = 70$ s. This is reasonable since T_1 is too short for the UAV relay to reach the optimal relay location of each source-destination pair, leaving the UAV to relay with limited conditions as much as possible. Instead, T_2 is enough for the UAV to arrive at the optimal relay location of each source-destination pair and hover for a while to enjoy the optimal relay conditions with a better transmission rate. Third, for the OFDMA-based user scheduling, when the power is fixed, the difference in average transmission rate between T_1 and T_2 is not as obvious as that of TDMA-based user scheduling. This is because both T_1 and T_2 are sufficient for the UAV to arrive the center of all source-destination pairs where it can relay under good conditions. Last but not the least, it is observed that the average transmission rate of our proposed TDMA-based user scheduling is far better than that of the traditional OFDMA-based user scheduling when both time and distance are the same.

V. Conclusion

In this paper, we investigated FD-based UAV relaying for multiple source-destination pairs. To achieve effective multiple access for multiple source-destination pairs, we adopted a TDMA-based scheduling protocol to serve different source-destination pairs in turns. Different from the FDM-based protocol used in recent works that serve multiple source-destination pairs simultaneously with fixed UAV position or trajectory, the provided TDMA-based user scheduling protocol can significantly improve network throughput. We also formulated and solved a joint optimization problem to maximize the throughput performance of the network in terms of the TDMA-based user scheduling and the dynamic UAV trajectory. Simulation results demonstrate that our proposed scheme achieves significant improvement in network throughput.

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