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Research Article

Joint Deployment and Power Optimization for UAV Relay in Multiuser Networks

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Within the UAV network, the UAV first receives signals from multiple remote mobile devices (MDs) and then amplifies and forwards the transmitted signals to the base station (BS) with different amplification coefficients to form a UAV relay multiuser network. In this paper, we propose a new method to solve the problem of maximizing the throughput of the relay network. The proposed problem is decoupled into two subproblems, UAV deployment design and amplification coefficient optimization, to be solved iteratively, respectively. We solve the UAV deployment problem by adjusting its trajectory with a gradient descent-based method and solve the amplification coefficient subproblem with a convex optimization-based method iteratively. Simulation shows that the proposed UAV deployment and amplification coefficient of the UAV optimization design algorithm significantly improves the sum-rate compared with existing fixed relay and equal power allocation schemes. Finally, we discuss future potential performance enhancing methods including multiple UAV cooperation, massive multi-input multioutput (MIMO) communications, and nonorthogonal multiple access (NOMA) communications.

1. Introduction

The unmanned aerial vehicle (UAV) is becoming a promising technique that can be widely used in various scenarios, such as civil, emergency rescue, and military services [1]. Owning to its flexible deployment, high mobility, and low operational costs, the UAV has gained increasing popularity in the use of wireless networks [2] and has been formally discussed in the Third Generation Partnership Project (3GPP) specifications [3]. Applications in which UAVs significantly outperform terrestrial facilities include wireless coverage extension, remote sensing, and search and rescue [4].

UAVs are drawing significant attention in wireless networks to provide low-latency and easy-access wireless services by working as mobile relays in the above applications. Relevant reports indicate that, by the end of 2021, more than 29 million UAVs have been deployed [5]. In UAV relay networks, UAVs can be dynamically deployed at the optimal locations for serving high-mobility users [6]. UAV relays can also be deployed in emergency networks to keep user nodes in service in disasters [7].

Several recent works have explored the network performance improvement brought by the high mobility in UAV relay networks. In [8], the authors studied the downlink sum-rate maximization problem of a UAV relay network and designed the UAV trajectory and power allocation. In [9], the outage probability of UAV relay network was derived, and a trajectory design and power allocation method was proposed. In [10], the deployment and routing of the ad hoc-based UAV relay network were studied to reduce the transmission latency. In [11], the authors proposed a hybrid network architecture by leveraging the use of UAV as an aerial mobile base station (BS) to offload traffic from ground BSs; a joint UAV trajectory, bandwidth allocation, and user partitioning algorithm was proposed to maximize the sum-rate of the network. A UAV that works as a relay to collect data from ground sensor nodes was studied in [12], and a joint design of UAV trajectory and communication scheduling method was proposed. A UAV-assisted URLLC service system where the blocklength of channel codes is finite was studied in [13] with the constraint of uplink energy of the sensor nodes. However, the above works either consider the UAV as a BS and omit the performance of the fronthaul link to the core network or consider the UAV as a data collector that receives data from users one by one, which is different from the working scheme of cellular relays. As a result, the above solutions and simulations may have a large gap to the realistic UAV relay networks [14, 15].

In this paper, we consider an uplink UAV amplify-and-forward (AF) relay network with a UAV, a BS, and multiple mobile devices (MDs). Unlike the existing works [8–13], we study the sum-rate maximization problem by adopting the unique air-to-ground model and considering the performance of the MD-UAV link and the UAV-BS link jointly. We formulate this performance maximum problem to a joint UAV deployment and amplification coefficient optimization problem and design an iterative algorithm to solve the nonconvex problems effectively. The analyses on the proposed algorithm in terms of convergency and complexity are also studied. The proposed algorithm can also be applied in multi-UAV scenarios, where the interference management should also be considered. Since the interference caused by the UAV relay is similar to that of the UAV working as BSs, the interference management can be solved by existing works as proposed in [16]. In addition, some extensive scenarios of UAV relay communications are introduced in this paper, and some corresponding open problems and potential solutions are discussed, as illustrated below:

(1) Cooperative UAV relay network: cooperative UAVs are capable to extend the coverage of the relay network owing to their flexible deployment. To reduce power consumption and interference, the trajectory and radio resource management of the UAVs can be designed jointly

(2) Millimeter-wave (mmWave) UAV relay network: the emerging mmWave technique enables narrow beam transmission for the air-to-ground communications, which not only enhances the strength of receive signal but also avoids severe interference caused by the high probability of LoS links between the UAVs and MDs

(3) Nonorthogonal multiple access (NOMA) for UAV relay network: NOMA can be utilized in the mmWave UAV relay network to provide high throughput and massive connectivity. With proper beamforming in the mmWave communication system, MD pairs with significant channel gain differences can obtain significant uplink transmission rate gain when compared with orthogonal multiple access (OMA) communications

The rest of this paper is organized as follows. In Section 2, the system model and the sum-rate maximization problem are described and formulated, respectively. In Section 3, a joint UAV deployment and amplification coefficient optimization algorithm is given to solve the formulated problem. Simulation results are presented in Section 4, and the extensive scenarios of the UAV relay communications are described in Section 5. Finally, the conclusion of this paper is summarized in Section 6.

The notations used in this paper are listed in Table 1 for ease of reference.

2. System Model and Problem Formulation

As shown in Figure 1, we consider a cellular network with one BS and K MDs. The MDs, marked as $K = \{1, 2, \cdots, K\}$, are acquired to perform uplink transmissions to the BS; however, these MDs are beyond the coverage of the BS. To provide service coverage for the K MDs, a UAV is used as an AF relay between the BS and MDs. The high mobility of the UAV enables that it can dynamically adjust its location according to the distribution of the MDs to improve the quality of services (QoS) for the MDs. We assume that the transmission process contains T time slots, and the uplink transmission is performed in every two consecutive time slots. In the first time slot, the UAV receives uplink data from the K MDs. In the second time slot, the UAV amplifies the received signals and forwards them to the BS. We denote the positions of BS and MD i by B and M_i, respectively.

In time slot t, we denote the location of the BS by $(0, 0, H)$, the location of MD i by $l_i(t) = (x_i(t), y_i(t), 0)$, and the location of the UAV by $L(t) = (X(t), Y(t), H(t))$. The distance between the UAV and BS and the distance between the MD i and UAV are given by $d_{\mathrm{B}}^t = |L(t) - (0, 0, H)|$ and $d_i^t = |l_i(t) - L(t)|$, respectively. We denote the UAV speed in time slot t by $v(t)$, which is no more than the maximum UAV speed $v_{\max}$.

The air-to-ground propagation model proposed in [17, 18] is utilized to describe the MD-UAV and UAV-BS transmissions. To study the average performance of the network, this paper only focuses on the large-scale fading of the transmission links, while the small-scale fading can be omitted.

The channel model contains two parts: line-of-sight (LoS) path loss and non-line-of-sight (NLoS) path loss. In time slot t, the LoS and NLoS path loss models between the UAV and MD i in dB are given by

$$P_{\mathrm{L}}^{i,t} = L_{\mathrm{FS}} + 20 \log \left(d_i^t\right) + \eta_{\mathrm{LoS}}, \tag{1}$$

$$\mathrm{PL}_{\mathrm{N}}^{i,t} = L_{\mathrm{FS}} + 20 \log \left(d_i^t\right) + \eta_{\mathrm{NLoS}}, \tag{2}$$

where L_{FS} is the free space path loss given by $L_{\mathrm{FS}} = 20 \log (f) + 20 \log (4\pi/c)$, and f is the system carrier frequency. η_{LoS} and η_{NLoS} are additional attenuation factors due to the LoS and NLoS connections. This model assumes that all the antennas on the BS, UAV, and MDs are vertically deployed. Based on these assumption, the LoS connection probability is as follows:

$$\mathrm{Pr}_{\mathrm{L}}^{i,t} = \left(1 + \alpha \exp \left(-\beta\left(\phi^{i,t} - \alpha\right)\right)\right)^{-1}, \tag{3}$$

In the equation, α and β are environmental parameters, and $\phi^{i,t} = \sin^{-1}(H/d_i^t)$ is the elevation angle. The average large-scale path loss can then be expressed as

$$\mathrm{PL}_i^t = 10^{\left(\mathrm{Pr}_{\mathrm{L}}^{i,t} \times \mathrm{PL}_{\mathrm{L}}^{i,t} + \mathrm{Pr}_{\mathrm{N}}^{i,t} \times \mathrm{PL}_{\mathrm{N}}^{i,t}\right)/10}, \tag{4}$$

where $\mathrm{Pr}_{\mathrm{N}}^{i,t} = 1 - \mathrm{Pr}_{\mathrm{L}}^{i,t}$. In this paper, We assume the transmission power of each MD is fixed as a constant PT, and there is

Table 1: Notations.

Symbol	Description
$L(t)$	Location of UAV in time slot t
d_i^t	Distance between MD i and UAV
$v_{\max}$	Maximum UAV speed
d_{B}^t	Distance between UAV and BS
$P_{\mathrm{L}}^{i,t}$	LoS path loss
$\mathrm{PL}_{\mathrm{N}}^{i,t}$	NLoS path loss
$\mathrm{Pr}_{\mathrm{L}}^{i,t}$	Probability of LoS connection
$\mathrm{Pr}_{\mathrm{N}}^{i,t}$	Probability of NLoS connection
$P_{i,\mathrm{U}}^t$	Received power of the UAV from MD i
P_{T}	MD transmission power
N_0	Noise variance
G_i^t	UAV amplification coefficient for MD i's signal
$P_{i,\mathrm{B}}^t$	Transmission power of UAV for MD i's signal
P_{UAV}	Maximum transmit power of the UAV
$\mathrm{PL}_{\mathrm{B}}^t$	Average path loss of UAV-BS transmission
PL_i^t	Average path loss of MD i-UAV transmission
$P_{\mathrm{B},i}^t$	Received power of the BS of MD i's signal
γ_i^t	SNR of the MD i-BS link
R_i^t	Data rate of the MD i-BS link
W	Bandwidth

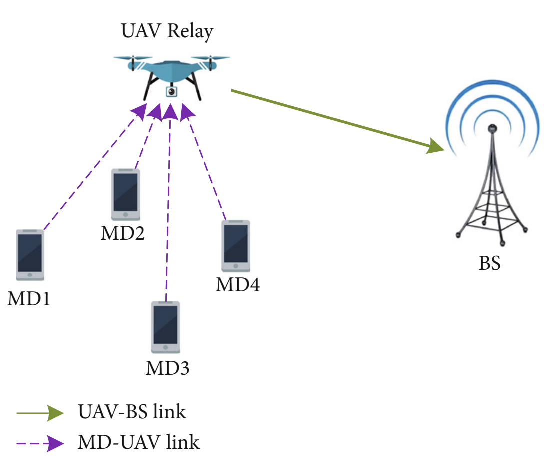

Figure 1: System model for AF-UAV relay-assisted multi-MD uplink communication.

no power control of MDs. The average received power of the UAV from MD i is given by

$$P_{i,\mathrm{U}}^t = \frac{P_{\mathrm{T}}}{\mathrm{PL}_i^t}, \tag{5}$$

where P_{T} is the transmission power of each MD, which can be considered as a content. The received signal of UAV relay from MD i is expressed as

$$y_{i,\mathrm{U}}^t = \sqrt{P_{\mathrm{T}}\mathrm{PL}_i^t} X_i^t + n_{\mathrm{U}}^t, \tag{6}$$

where X_i^t is the signal of unit energy from MD i and n_{U}^t is the additive white Gaussian noise (AWGN) received at the UAV relay, which satisfies Gaussian distribution with zero mean and N_0 as variance.

After receiving the signals from the MDs, the signals are amplified and forwarded to the BS by the UAV relay. We assume that the communication link for each MD occupies an independent channel, and there is no interchannel interference. In time slot t, let G_i^t be the signal amplification coefficient of the UAV relay for MD i's signal and $P_{i,\mathrm{B}}^t$ be the transmission power of the UAV relay for MD i's signal. The following relation holds:

$$P_{i,\mathrm{B}}^t = \left(G_i^t\right)^2 \left(P_{i,\mathrm{U}}^t + N_0\right). \tag{7}$$

We assume that the maximum transmit power of the UAV is P_{UAV}. Therefore, the signal amplification coefficients for all the MDs satisfy

$$\sum_{i=1}^{K} \left(G_i^t\right)^2 \left(\frac{P_{\mathrm{T}}}{\mathrm{PL}_i^t} + N_0\right) \le P_{\mathrm{UAV}}, \tag{8}$$

where N_0 is the AWGN power.

Similar to the MD-UAV transmission, the UAV-BS transmission also follows the air-to-ground channel model. We denote the average large-scale path loss of the UAV-BS transmission by $\mathrm{PL}_{\mathrm{B}}^t$, which can also be obtained by equations (1)–(4). The received power of the BS of MD i's signal can be expressed as

$$P_{\mathrm{B},i}^t = \frac{P_{i,\mathrm{B}}^t}{\mathrm{PL}_{\mathrm{B}}^t}. \tag{9}$$

The received signal from MD i to the BS can be expressed as

$$y_{i,\mathrm{B}}^t = G_i^t \sqrt{\frac{P_{\mathrm{T}}}{\mathrm{PL}_i^t \mathrm{PL}_{\mathrm{B}}^t}} X_i^t + \frac{G_i^t n_{\mathrm{U}}^t}{\sqrt{\mathrm{PL}_{\mathrm{B}}^t}} + n_{\mathrm{B}}^t, \tag{10}$$

where n_{B}^t is the noise received at the BS. According to (10), the joint signal-to-noise ratio (SNR) of the two-step uplink transmission between MD i and the BS is given by

$$\gamma_i^t = \frac{P_{\mathrm{T}}\left(G_i^t\right)^2 / \mathrm{PL}_i^t \mathrm{PL}_{\mathrm{B}}^t}{\left(G_i^t\right)^2 N_0 / \mathrm{PL}_{\mathrm{B}}^t + N_0}. \tag{11}$$

The data rate of the uplink transmission from MD i to the BS can be expressed as

$$R_i^t = W \log_2\left(1 + \gamma_i^t\right), \tag{12}$$

where W is the bandwidth that can be considered as fixed value.

Our objective is to maximize the sum-rate of all the MDs by optimizing both the UAV deployment $\mathscr{L} = \{L(t)\}$ and the amplification coefficients $\mathscr{G}=\{G_i^t\}, i=1,\cdots K$ for K MDs in T time slots. The problem can be formulated by

$$\min_{\mathscr{L},\mathscr{G}} \quad \sum_{t=1}^{T}\sum_{i=1}^{K} R_i^t \tag{13a}$$

$$\text{s.t.} \quad \sum_{i=1}^{K}\left(G_i^t\right)^2\left(\frac{P_\mathrm{T}}{\mathrm{PL}_i^t}+N_0\right)\le P_\mathrm{UAV}, \quad t=1,\cdots,T \tag{13b}$$

$$G_i^t\ge 0, \quad t=1,\cdots,T, i=1,\cdots K \tag{13c}$$

$$v(t)\le v_{\max}, \tag{13d}$$

where (13b) and (13c) are the power constraints for UAV and MD and (13d) shows the UAV mobility constraint.

3. UAV Deployment and Amplification Coefficient Optimization

This section proposes a solution to the aforementioned problem of optimizing the deployment of UAV relay and amplification coefficients for the MDs jointly. Problem (13) is nonconvex with respect to $\mathscr{L}$ and $\mathscr{G}$. To solve this problem, we decouple (13) into two subproblems: UAV deployment and amplification coefficient optimization, and propose an iterative algorithm to solve them jointly. The convergency and complexity analyses are then followed.

3.1. UAV Deployment. In this part, we consider the amplification coefficients to be fixed and design the deployment of the UAV. The subproblem can be shown as

$$\min_{\mathscr{L}} \quad \sum_{t=1}^{T}\sum_{i=1}^{K} R_i^t \tag{14a}$$

$$\text{s.t.} \quad v(t)\le v_{\max} \tag{14b}$$

To solve problem (14), we first discuss the convexity of the sum-rate with respect to the location of the UAV.

Theorem 1. *The sum-rate of all the MDs is a concave function with respect to the location of the UAV approximately.*

Proof. See the appendix. □

To achieve the optimal UAV deployment, we propose a gradient ascent method as follows. Since the maximum UAV velocity in each time slot $v_{\max}$ is much shorter than the transmission distance d_i^t and d_B^t, we first set the UAV velocity as $v(t)=v_{\max}$. We assume that the UAV is at a random location $L^0(t)=(X^0(t),Y^0(t),H^0(t))$ initially and adjusts its location in a sequence of time slots. In each time slot, the UAV is moved along the direction with the maximum sum-rate ascent velocity, i.e.,$\nabla\sum_{i=1}^K R_i^t=((\sum_{i=1}^K \partial R_i^t)/\partial x|_{y=Y^0(t),h=H^0(t)}, (\sum_{i=1}^K \partial R_i^t)/\partial y|_{x=X^0(t),h=H^0(t)}, (\sum_{i=1}^K \partial R_i^t)/\partial h|_{x=X^0(t),y=Y^0(t)})$. The location of the UAV is then adjusted to $L^1(t)=(X^1(t),Y^1(t),H^1(t))$, with $X^1(t)=X^0(t)+v|(\sum_{i=1}^K \partial R_i^t)/\partial x|^2/(|(\sum_{i=1}^K \partial R_i^t)/\partial x|^2+|(\sum_{i=1}^K \partial R_i^t)/\partial y|^2+|(\sum_{i=1}^K \partial R_i^t)/\partial h|^2)$, $Y^1(t)=Y^0(t)+v|(\sum_{i=1}^K \partial R_i^t)/\partial y|^2/(|(\sum_{i=1}^K \partial R_i^t)/\partial x|^2+|(\sum_{i=1}^K \partial R_i^t)/\partial y|^2+|(\sum_{i=1}^K \partial R_i^t)/\partial h|^2)$, and $H^1(t)=H^0(t)+v|(\sum_{i=1}^K \partial R_i^t)/\partial h|^2/(|(\sum_{i=1}^K \partial R_i^t)/\partial x|^2+|(\sum_{i=1}^K \partial R_i^t)/\partial y|^2+|(\sum_{i=1}^K \partial R_i^t)/\partial h|^2)$. We also set a minimum gradient threshold $\delta\longrightarrow 0^+$. When $\nabla\sum_{i=1}^K R_i^t<\delta$, it is regarded that the maximum sum-rate is achieved, and the UAV hovers at the optimal location.

Since $\sum_{i=1}^K R_i^t$ is a concave function with respect to the location of the UAV, when the locations of the MDs are assumed to be fixed, the UAV can approach the optimal location in finite time slots, with the error being no larger than v. If the locations of the MDs are not fixed, the UAV adjusts the direction of the gradient dynamically according to the locations of the MDs in the current time slot.

3.2. Amplification Coefficient Optimization. In this part, we design the amplification coefficients in each time slot, with the location of the UAV $L(t)$ given. The amplification coefficient subproblem can be given as

$$\min_{\mathscr{G}} \quad \sum_{i=1}^{K} R_i^t \tag{15a}$$

$$\text{s.t.} \quad \sum_{i=1}^{K}\left(G_i^t\right)^2\left(\frac{P_\mathrm{T}}{\mathrm{PL}_i^t}+N_0\right)\le P_\mathrm{UAV}, \quad t=1,\cdots,T \tag{15b}$$

$$G_i^t\ge 0, \quad t=1,\cdots,T, i=1,\cdots K \tag{15c}$$

As shown in (7), variable G_i^t is a function of $P_{\mathrm{U},i}^t$ when the locations between the UAV and MD i are given. Therefore, problem (15) can be converted to the following UAV transmission power optimization problem

$$\min_{P_{\mathrm{U},i}^t} \quad \sum_{i=1}^{K} R_i^t \tag{16a}$$

$$\text{s.t.} \quad \sum_{i=1}^{K} P_{i,\mathrm{B}}^t\le P_\mathrm{UAV}, \quad t=1,\cdots,T \tag{16b}$$

$$P_{i,\mathrm{B}}^t\ge 0, \quad t=1,\cdots,T, i=1,\cdots K \tag{16c}$$

Problem (16) is convex and can be solved with water filling algorithm proposed in [19]. The optimal power allocation strategy can be expressed as

$$P_{i,\mathrm{B}}^{t,\mathrm{opt}}=\left[\lambda-\frac{1}{\mathscr{H}_i/N_0}\right]^+, \tag{17}$$

where

$$\mathscr{H}_i=\frac{P_\mathrm{T}/\mathrm{PL}_i^t\mathrm{PL}_\mathrm{B}^t}{N_0/\mathrm{PL}_\mathrm{B}^t+N_0\left(P_\mathrm{T}/\mathrm{PL}_i^t+N_0\right)} \tag{18}$$

is the equivalent channel gain of the MD-UAV-BS link, and

$$\lambda=\frac{1}{K}\left(P_\mathrm{UAV}+\sum_{i=1}^{K}\frac{1}{\mathscr{H}_i/N_0}\right) \tag{19}$$

is the water-filling level. The optimal amplification coefficient is solved as

$$G_i^{t,\mathrm{opt}} = \sqrt{\frac{P_{i,\mathrm{B}}^{t,\mathrm{opt}}}{P_\mathrm{T}/\mathrm{PL}_i^t + N_0}} \tag{20}$$

3.3. Algorithm Summary. In this part, the proposed algorithm that jointly optimizes UAV deployment and amplification coefficients is summarized as follows. In each iteration, give the initial location of the UAV, and the optimal amplification coefficients can be solved as proposed in Section 3.2. Afterwards, the UAV deployment is adjusted by moving along its trajectory as proposed in Section 3.1 with the amplification coefficients given. We then update the location of the UAV for the amplification coefficient optimization accordingly. Since the transmission distance is much larger than the moving distance of the UAV in one iteration, the performance degradation of the amplification coefficient optimization caused by the change of the UAV location in one iteration can be neglected. Iterations of amplification coefficient optimization and UAV deployment design are proposed until the performance gain of an iteration is less than a threshold ω. The joint UAV deployment and amplification coefficient optimization algorithm is summarized in Algorithm 1. We denote the sum-rate of the network after the rth iteration by $\mathscr{R}(\mathscr{L}^r, \mathscr{G}^r)$.

3.4. Algorithm Analysis. In this part, we analyse the convergency and complexity of the proposed algorithm.

Theorem 2. *The proposed UAV deployment and amplification coefficient optimization algorithm is convergent.*

Proof. In the $(r+1)$th iteration, we first find the optimal solution to the amplification coefficients with the location of the UAV being $\mathscr{L}^r$. Therefore, we have

$$\mathscr{R}\left(\mathscr{L}^r, \mathscr{G}^{r+1}\right) \geq \mathscr{R}(\mathscr{L}^r, \mathscr{G}^r), \tag{21}$$

i.e., the sum-rate does not decrease with amplification coefficient optimization in the $(r+1)$th iteration. When designing the UAV deployment, we give the optimal UAV moving trajectory $\mathscr{L}^{r+1}$ with the amplification coefficients being $\mathscr{G}^{r+1}$, and thus, we have

$$\mathscr{R}\left(\mathscr{L}^{r+1}, \mathscr{G}^{r+1}\right) \geq \mathscr{R}\left(\mathscr{L}^r, \mathscr{G}^{r+1}\right). \tag{22}$$

□

Combining (2) and (2), we have the following inequation:

$$\mathscr{R}\left(\mathscr{L}^{r+1}, \mathscr{G}^{r+1}\right) \geq \mathscr{R}\left(\mathscr{L}^r, \mathscr{G}^{r+1}\right) \geq \mathscr{R}(\mathscr{L}^r, \mathscr{G}^r). \tag{23}$$

As shown in (2), in each iteration, the objective function does not decrease. In the meanwhile, such a network has a capacity bound, and the uplink sum-rate cannot increase unlimitedly with iterations of deployment design and amplification coefficient optimization. Therefore, the objective function is upper-bounded and will converge to a stable solution in limited iterations; i.e., the proposed UAV deployment and amplification coefficient optimization algorithm is convergent.

Theorem 3. *The complexity of the proposed UAV deployment and amplification coefficient optimization algorithm is $O(K^2T)$.*

Proof. In each time slot, the proposed UAV deployment and amplification coefficient optimization algorithm contains iterations of UAV deployment design and amplification coefficient optimization. In each iteration, the complexity of UAV deployment design, i.e., finding the gradient descent direction, is $O(1)$, while the complexity of the amplification coefficient optimization, i.e., the convex optimization progress, can be minimized to $O(K)$ [20]. Therefore, the complexity of each iteration is $O(K)$. The number of iterations in each time slot is determined by the sum-rate improvement in each iteration and the total sum-rate improvement. The sum-rate improvement in each iteration is no less than the given threshold δ, while the total sum-rate improvement is no more than linear, i.e., $O(K)$, with respect to the number of the MDs. In summary, the number of iterations increases no more than linear, i.e., $O(K)$, with respect to the number of the MDs. Therefore, the complexity of the proposed UAV deployment and amplification coefficient optimization algorithm in T time slots is $O(K) \times O(K) \times O(T) = O(K^2T)$. □

4. Simulation Results

In this section, the performance of Algorithm 1 is evaluated with simulations. We select the simulation parameters based on the 3GPP specification basis [3] and related existing works. The values of the key parameters in the simulation are listed in Table 2. The simulation is performed in Monte Carlo scheme, with each curve generated by averaging the results of 10^5 instances.

We provide three schemes in comparison with the proposed scheme: fixed location relay scheme, circular trajectory relay scheme, and equal power scheme. In the fixed location relay scheme, the UAV stays at the initial location in every time slot. In the circular trajectory relay scheme, the trajectory is a circle whose center is (250, 0, 0) and radium is 100. The initial location of UAV is a random point on this circle and the moving distance is 1 meter for a time slot. The amplification coefficient design is the same as our proposed algorithm. In the equal power scheme, the transmit power of the UAV is equally allocated to every user, regardless of the channel quality, and the UAV deployment is designed the same as the proposed scheme.

Figure 2 depicts the average sum-rate of different schemes with time axis. The sum-rate of the network increases with the location adjustment of the UAV and converges to the maximum value in about 350 time slots. The proposed UAV deployment can improve the sum-rate for about 80% when compared with the fixed location relay and is about 15 bit/s/Hz higher than the equal power scheme. When compared with the circular trajectory scheme, the proposed algorithm

1: **Initialize** Obtain the initial location of the UAV and the MDs
2: **While** $\mathscr{R}(\mathscr{L}^r, \mathscr{G}^r) - \mathscr{R}(\mathscr{L}^{r-1}, \mathscr{G}^{r-1}) > \omega$
3: **If** $\nabla \sum_{i=1}^{K} R_i^t \geq \delta$
4: Solve amplification coefficient optimization subproblem (15) for time slot t;
5: Solve UAV deployment optimization subproblem (15) for time slot t
6: Update the UAV location and the MDs' locations;

Algorithm 1: Joint UAV deployment and amplification coefficient optimization algorithm.

Table 2: Simulation parameters.

Variable	Value
Total time slots T	500
Number of MDs K	10
MD distribution range	$100 \times 100\,\mathrm{m}^2$
Average distance between the MDs and BS	500 m
BS location	0, 0, 50
Initial location of the UAV	0, 0, 100
Maximum UAV speed $v_{\max}$	1 m per time slot
Algorithm convergency threshold δ	-10^{-2}
Maximum UAV transmission power P_{UAV}	26 dBm
Noise variance N_0	-76 dBm
Path loss parameter η_{LoS}	1
Path loss parameter η_{NLoS}	20
Path loss parameter α	12
Path loss parameter β	0.135

improves the sum-rate for about 40% on average. The sum-rate performance of the proposed algorithm converges faster than the equal power one, which shows that the UAV can be more rapidly deployed with the proposed algorithm.

In Figure 3, we study the scenario with MDs moving randomly on the ground. The sum-rate is illustrated with different average MD speeds v_{MD}. It is shown that when the MD mobility is much lower than that of the UAV, the sum-rate of the network tends to converge to that of the static MDs, but with a longer time. When the mobility of the MDs is comparable to the UAV, the sum-rate of the network cannot converge to that of the static MDs because of the rapid variation of the optimal UAV location. However, the sum-rate can still be 60% higher than that of the fixed location relay, due to the proposed UAV deployment design method.

5. Extensions of UAV Relay Networks

After discussing the design of the UAV deployment and amplification coefficients, we present several promising study directions of UAV relay networks in this section. Three extensive scenarios, together with the corresponding open problems and potential solutions are listed below.

5.1. Cooperative UAV Relay Network. One promising study of the UAV relay network is the UAV cooperative relay communication design, in which multiple relay UAVs perform transmission cooperatively in a multihop mode. A cooperative UAV relay enables long distance transmission with high QoS requirements. In the rapid developing Internet of Things (IoT) networks, various applications with large data rate and long transmission distance requirements are emerging, e.g., live video streaming and extended reality. Such applications raise challenges on the conventional terrestrial cellular network for two reasons. First, the severe shadowing leads to a high probability of NLoS transmissions in terrestrial network. It is more difficult for the terrestrial relays to find a LoS transmission path than the UAV relay network, thus leading to higher large-scale fading. Second, the terrestrial relays are fixed or with low mobility, which are incapable to improve the transmission QoS by adjusting their locations dynamically. The UAV relay communication provides more flexible deployment and high LoS transmission possibility, thus improving the service coverage and transmission rate of the network.

By bringing in cooperative UAV relay communications into IoT networks, some new study aspects need to be further studied. Unlike the terrestrial communications in wireless sensing networks, the topology of the cooperative UAV relay network changes rapidly. Therefore, works on designing the routing protocol that suits the rapid changing topology of the cooperative UAVs should be further discussed. Recently, the designs of multihop transmission routing protocols for the cooperative UAV relays are emerging [21, 22]. However, most of the proposed protocols in existing works are heuristic, and the deep analysis on the routing protocol that considers the UAV buffer and onboard energy jointly has not been well discussed, which has the potential to significantly affect the performance in practical systems. In future works, the protocol that jointly considers the physical constraints and UAV deployment can be designed.

5.2. mmWave UAV Relay Network. mmWave has been considered as one of the most important evolution directions in 5G and the upcoming 6G networks [23]. It offers a high integration of massive antennas that enables electronically steerable and highly directional beamforming, thus mitigating the interference for UAV communications [24], as multiple MDs can access the channel concurrently and be separated by spacial beams [25]. In this way, the interference can be eliminated, and the sum-rate can be significantly improved given the ultrawide mmWave bandwidth. To be specific, to obtain spacial diversity gain in multiantenna system, the distance between two antennas should be no less than half of the wavelength. In mmWave communications,

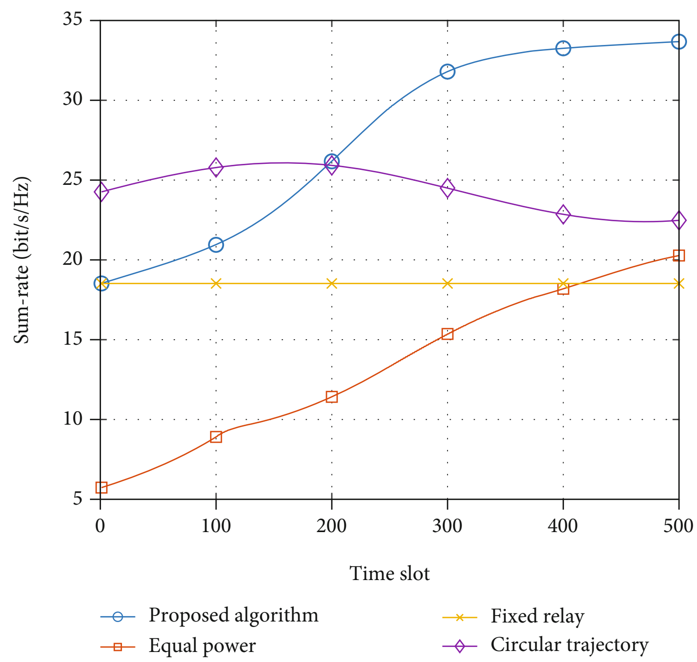

Figure 2: Sum-rate of different schemes.

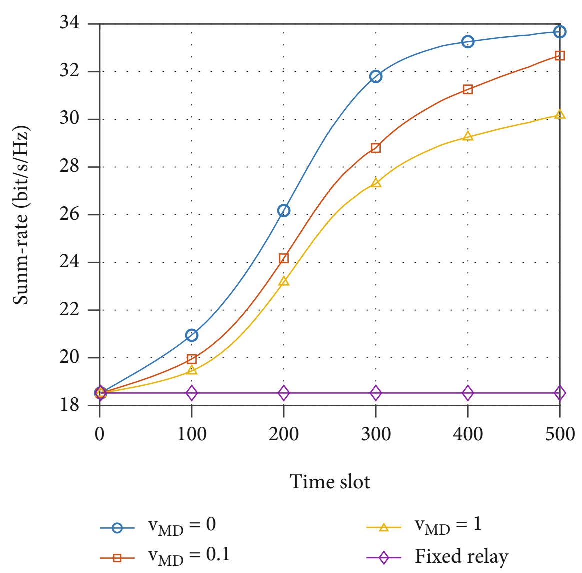

Figure 3: Sum-rate of different MD speeds.

the antennas can be much closer to each other than those in the conventional sub-6G systems, owning to a much shorter transmission wavelength. On this condition, a massive antenna array can be integrated in a small area, which is appropriate for UAV relays with strict space limitation. The massive antenna array is capable to achieve high array gain and reduce the propagation loss of the transmission links. For the above reasons, mmWave communications can strongly support the UAV relay communications with beamforming technique [26].

In addition to the beamforming technique and ultra-wide-spectrum resources, mmWave UAV communications have a few additional advantages. Due to the characteristic of weak scattering in the mmWave band, the mmWave channel has better performance of sparsity and directivity when compared with sub-6G communications. In particular, the LoS path is longstanding for the UAV relays with high altitude and can be actively created on demand via the movement of UAVs. The LoS component of the transmission links can be over 20 dB higher than that of the NLoS ones. Thus, the mmWave communications with directional beamforming give full play to the advantages of the LoS transmission paths for UAV relays. Moreover, the dynamic beam direction of the mmWave communications enables the highly mobile UAVs to adjust the transmission and reception timely, in order to obtain higher channel gain than that of the conventional full coverage scheme. Thus, the mmWave UAV relay communications have the capability to increase spectrum efficiency of the network. The above-mentioned beamforming, interference management, and spectrum efficiency improvement problems are promising studies in the mmWave UAV relay networks, which can be further studied in the upcoming researches.

5.3. NOMA for UAV Relay Network. The ultrahigh MD density poses huge pressure on the limited number of subbands in mmWave communications and the sparsity of UAV relay deployment. As a result, the OMA scheme may suffer severe congestion risks when massive MDs intend to perform data upload simultaneously. To tackle the challenges of access collision reduction and massive connectivity, NOMA has been raised as a promising solution, which allows the MDs to access the radio resources nonorthogonally. It is especially helpful in the uplink transmission in mmWave UAV relay communication system. As introduced in [27], NOMA achieves considerable performance gain when the channel gains of a paired MDs differs significantly. In the mmWave UAV relay network, UAV relays can adjust their reception beams for a pair of uplink MDs to construct such a channel gain difference, thus fully exploring the potential performance gain of NOMA technique.

NOMA can be utilized in the UAV relay communications in massive connectivity scenarios, where multiple MDs access the channel nonorthogonally by either code domain [28] or power domain [29] multiplexing. Multiple MDs can improve the spectrum efficiency and sum-rate of the network by performing concurrent transmissions on the same channel. In order to cope with the cochannel interference in the nonorthogonal scheme, multiuser detection techniques such as successive interference cancellation can be utilized in the receivers, with which the superposed signals can be decoupled and demodulated, thus making this system practical. Due to the air-to-ground communication properties and the high mobility of the UAVs, the study of NOMA for UAV relay networks is different from that of the terrestrial ones in many aspects, such as power control, spectrum management, and signaling control, which should be further studied in future works.

6. Conclusions

In this paper, we consider that a multi-MD uplink network with a relay UAV amplifies and forwards the signals from the MDs to the BS with different amplification coefficients. With UAV speed and power constraints, a joint optimization to the UAV deployment design and amplification coefficient design is given. This paper analysed the convergence and complexity of the proposed algorithm. Simulation result shows that the sum-rate of the proposed solution outperforms fixed location relay and equal power allocation schemes significantly and can improve the sum-rate of mobile MDs. This paper also discussed the extensions and open problems of UAV relay communications based on the model of this paper, including UAV cooperation, mmWave, and NOMA.

Appendix

A.1. Proof of Theorem 1

Proof. According to (1) and (2), the path loss of the air-to-ground communication is negatively quadratic related to the transmission distance. Therefore, we consider the change of the path loss as a negatively quadratical function of the transmission distances, i.e., $\mathrm{PL}_i^t \propto (d_i^t)^{-2}, (d_\mathrm{B}^t)^{-2}$. We then substitute (1) into (1), and the uplink data rate of MD i can be approximated as

$$R_i^t = W \log_2\left(1 + \frac{P_\mathrm{T}(d_i^t)^{-2}(G_i^t)^2(d_\mathrm{B}^t)^{-2}}{N_0(G_i^t)^2(d_\mathrm{B}^t)^{-2} + N_0}\right). \tag{24}$$

□

It is shown in (2) that R_i^t is negatively related with both d_i^t and d_B^t. Therefore, the maximum value of R_i^t is achieved when $d_i^t + d_\mathrm{B}^t$ is minimized. Otherwise, the value of R_i^t can be improved by reducing the value of d_i^t or d_B^t. Let L be the minimum value of $d_i^t + d_\mathrm{B}^t$; when R_i^t is maximized, we have $d_\mathrm{B}^t = L - d_i^t$. When we substitute $d_\mathrm{B}^t = L - d_i^t$ into (2), R_i^t becomes a univariate function of d_i^t, which can be expressed as

$$R_i^t = W \log_2\left(1 + \frac{P_\mathrm{T}(G_i^t)^2}{N_0(G_i^t)^2(d_i^t)^2 + N_0(d_i^t)^2(L - d_i^t)^2}\right). \tag{25}$$

The derivative of R_i^t with respect to d_i^t is given as

$$\frac{dR_i^t}{d(d_i^t)} = \frac{-WA'}{\ln 2\left(A + P_\mathrm{T}(G_i^t)^2\right)A}, \tag{26}$$

where

$$A = N_0 d_i^t\left((G_i^t)^2 + (L - d_i^t)^2\right), \tag{27}$$

$$A' = \frac{dA}{d(d_i^t)} = 4N_0(d_i^t)^3 - 6N_0(d_i^t)^2 L + 2N_0\left(L^2 + (G_i^t)^2\right)d_i^t. \tag{28}$$

The second-order derivative of R_i^t with respect to d_i^t is given as

$$\frac{d^2R_i^t}{d(d_i^t)^2} = \frac{-WP_\mathrm{T}(G_i^t)^2}{\ln 2} \times \frac{A''\left(A + P_\mathrm{T}(G_i^t)^2\right)A - A'\left(A'A + A'P_T(G_i^t)^2 + A'A\right)}{\left(A + P_\mathrm{T}(G_i^t)^2\right)^2 A^2}, \tag{29}$$

where

$$A'' = \frac{d^2A}{d(d_i^t)^2} = 12N_0(d_i^t)^2 - 12N_0 d_i^t L + 2N_0\left(L^2 + (G_i^t)^2\right). \tag{30}$$

We then substitute (27), (28), and (3) into (29), and it can be proved that $d^2R_i^t/d(d_i^t)^2 < 0$; i.e., the data rate of MD i is a concave function of the location of the UAV. According to the properties of concave function, the sum of all the uplink data rate $\sum_{i=1}^K R_i^t$ is also a concave function of the UAV deployment.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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