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Power and Trajectory Optimization for UAV-Enabled Amplify-and-Forward Relay Networks

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ABSTRACT Unmanned aerial vehicle (UAV) is suitable to improve connectivity of wireless communication networks in harsh environment due to its flexible deployment and high mobility. In this paper, we consider the case that a UAV is employed as a mobile relay to ferry data between two disconnected ground nodes. The amplify-and-forward mobile relay technique is studied. By exploiting the channel state variation induced by the movement of UAV, we consider maximizing the end-to-end throughput of this mobile relay system by optimizing the source/relay power allocation, as well as the UAV's trajectory. However, the formulated problem is non-convex and intractable to solve. To address this non-convex problem, we propose two iterative algorithms to optimize the source/relay power allocation with the fixed UAV's trajectory and the UAV's trajectory with fixed power allocation, by successive convex optimization, respectively. Then, an iterative algorithm is proposed to optimize the source/relay power allocation and UAV's trajectory in an alternate manner. By exploiting the predictable channel variation via the proposed power and trajectory optimization scheme, numerical results show that significant throughput gains can be achieved.

INDEX TERMS Mobile relay, power allocation, trajectory optimization, throughput maximization, UAV communication.

I. INTRODUCTION

Due to the cost reduction in unmanned aerial vehicle (UAV) and device miniaturization in communication equipment, UAVs have aroused a lot of attentions in wireless networks, such as information dissemination, relaying, data gathering, etc [1]. Compared to traditional wireless system deployed on the ground, UAV-enabled communication system is capable to provide line-of-sight (LOS) communication links with ground terminals, which results in better communication channels [2]. Besides, the high mobility of UAV makes UAV based systems more flexible to deploy. Therefore, UAVs equipped with communication transceivers are expected to be employed in various applications, including mobile relaying for emergency situations, information broadcasting and data collection in wireless sensor networks (WSNs), data offloading for cellular base stations in hotspot areas, etc.

Various research efforts have been devoted on UAV assisted wireless systems in recent years. Based on practical applications, some researches employ UAVs at fixed locations. In this case, the key problem is to find the optimal location for UAVs to satisfy various quality-of-service (QoS) requirements. In [3], by employing one rotary-wing UAV as relay to serve multiple communication pairs on the ground, the UAV's position, as well as transmission power, bandwidth were optimized jointly to maximize the system throughput. In [4], the optimum altitude of the UAV as a relaying station on the reliability metrics was analyzed. This work considers both hops from the ground user to UAV and from UAV to the remote station in the placement optimization. In [5], UAVs were employed as femtocell base stations hovering at assigned locations in temporary emergency networks for disaster scenarios. In [6], considering the characteristics of the PHY and MAC layers, as well as keeping all associated users within the transmission range of the UAV, the optimal position of a single UAV with respect to its associated users to maximize throughput was addressed. In [7], the issue of multiple UAVs deployed as aerial base stations to provide wireless service to ground users was studied. Two key practical scenarios, UAV communication under hover time constraints, and UAV communication under load constraints were investigated. In [8], UAVs were employed as mobile base stations to provide wireless connectivity. The minimum number of UAVs needed to provide wireless coverage for a group of distributed ground terminals was considered. In [9], the optimal position of UAV for relay establishment was studied. Without knowing ground unit positions, only the signal strength and its angle of arrival were employed as position information of ground units. In [10], UAV assisted secure transmission for scalable videos in hyper-dense networks via caching was studied. The principle of interference alignment was exploited to guarantee secure transmission in the presence of an eavesdropper.

By exploiting the high mobility of UAV, more degrees of freedom can be achieved in designing of UAV-enabled wireless systems. In this case, the UAV can move closer to the target ground user to obtain better channel. By exploiting carefully designed UAV trajectory, significant performance gains can be achieved compared to traditional wireless systems with fixed nodes on the ground. In [11], the trajectory of multiple small UAVs was studied to expanding communication links and improving communication quality for a fleet of naval vessels. By exploiting motion estimates of vessels and states of UAVs, the authors proposed a decentralized nonlinear model predictive trajectory planning strategy for a dynamic environment. In [12], a UAV path planning mechanism in accordance with sensing, energy, time, and risk utilities was proposed to acquit data over sensor networks. In [13], Zeng and Zhang studied the energy-efficient UAV communication with a ground terminal via optimizing the UAV's trajectory. Considering the requirements for QoS and ground terminal scheduling, the UAV the energy efficiency problem by trajectory optimization was extended to a group of distributed ground terminals in [14]. In [15], the problem of jointly optimizing the bit allocation for uplink and downlink communications as well as for computing at the UAV, along with the cloudlet's trajectory under latency and UAV's energy budget constraints was formulated and addressed. In [16], a UAV was dispatched to disseminate a common file to a set of ground terminals with a desired high probability. The UAV's trajectory was designed to minimize its mission completion time. In [17], the UAV trajectory at the edges of three adjacent cells to offload traffic for base stations was optimized to maximize the sum rate of UAV served edge users subject to the rate requirements for all the users.

Note that the communication channel between the UAV and the ground terminals varies along with the location of UAV. Thus the designation of mobile UAV based wireless communication system should consider the predictable channel variation induced by UAV movement. Some of the researches optimize the trajectory as well as other resources to improve the UAV-enabled wireless systems. In [18], a UAV was employed as relay to improve the connectivity between a mobile device and a base station. The trajectory and transmit power of UAV was optimized to minimize the outage probability of the relay network. In [19], multiple UAV-mounted aerial base stations were employed to serve a group of users on the ground. The multiuser communication scheduling and association jointly with the UAV's trajectory and power control were optimized to maximize the minimum throughput over all ground users in the downlink communication. In [20], throughput maximization problem in UAV-enabled relaying systems by optimizing the source/relay transmit power along with the relay trajectory was studied.

In this paper, we consider a UAV serving as a mobile relay to establish communication link between two isolated ground nodes. Although the decode-and-forward (DF) case has been studied in [20], amplify-and-forward (AF) strategy does not need to decode and re-encode the received information before transmission, which significantly simplifies its complexity. Besides, DF is a delay tolerant strategy whereas AF strategy is more suitable for realtime applications, such as establishing temporary communication links in emergency situations. Thus AF is more commonly used in many applications. In this work we study the AF relay situation. We aim to maximize the overall throughput by optimizing the UAV trajectory as well as the source/relay power allocation, which turns out to be a non-convex optimization problem. To address this non-convex problem, first we develop an iterative algorithm by successive convex optimization to optimize the source/relay power allocation with fixed UAV trajectory. Then we maximize the throughput by optimizing the UAV trajectory with given source/relay power allocation. Finally, the source/relay transmission power and the UAV trajectory were optimized alternately.

The rest of this paper is organized as follows. In Section II the system model of UAV-enabled wireless relay network is introduced. In Sections III we formulate the throughput maximization. Besides, the source/relay power allocation scheme with fixed UAV trajectory, the UAV trajectory planning scheme with fixed power allocation and the joint power allocation and trajectory planning scheme are proposed. Section IV presents the numerical results to demonstrate the performance of the proposed schemes. Conclusions of this paper are drawn in Section V.

II. SYSTEM MODEL

Consider a dual-hop mobile relay network, where a UAV is employed as a mobile relay to ferry data from source to the destination, which are denoted by A and B, respectively. A and B are deployed on the ground with fixed locations and the UAV flies at a fixed altitude h. We assume direct link between A and B is negligible due to severe blockage or long distance. For simplicity of analysis, we consider a Cartesian coordinate system shown in Fig. 1. Without loss of generality, we assume that A and B are located at $(0, 0, 0)$ and $(L, 0, 0)$, respectively. We consider the UAV flying as a mobile relay during time period T, thus the coordinate of UAV is $(x(t), y(t), h)$ with $0 < t < T$.

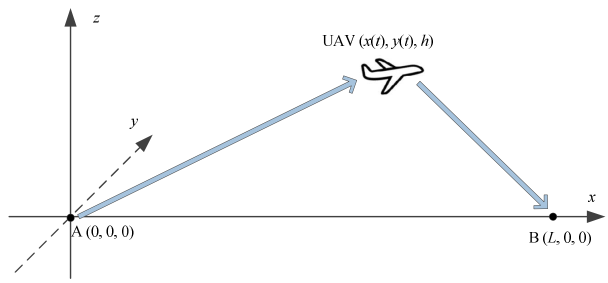

FIGURE 1. Geometrical model of the UAV-enabled AF relay system.

For simplicity of analysis, the time period T is divided into N equally spaced time slots. In this paper, N is chosen to be large enough so that at each time slot, the position of UAV is approximate constant. Thus the trajectory of UAV can be approximated by N discrete sequences, i.e. coordinates of UAV over time period T can be represented as $\{x[n], y[n], h\}_{n=1}^{N}$. For given UAV's maximum flying speed V, the maximum flying distance of UAV is VT/N in one time slot. The UAV's trajectory should satisfy

$$(x[n+1]-x[n])^2+(y[n+1]-y[n])^2 \leq \left(\frac{VT}{N}\right)^2 \quad n=1,2,\cdots,N-1. \tag{1}$$

At each time slot, the UAV ferries data in an amplify-and-forward (AF) manner; i.e., A transmits data to UAV during the first hop, the UAV amplifies the received signal and transmits it to B with a certain gain G during the second hop.

At the nth time slot, the received signal at UAV for the first hop can be expressed as

$$y_u[n] = \sqrt{p_a[n]h_{au}[n]}x_a[n] + z_1[n], \tag{2}$$

where $p_a[n]$ is the transmission power of A. $x_a[n]$ is the transmitted data at A with circularly symmetric complex Gaussian distribution $CN(0, 1)$. $z_1[n]$ is the additive white Gaussian noise (AWGN) observed at UAV. Thus $z_1[n]$ follows $CN(0, N_1)$. We assume the communication channel between ground nodes and UAV is line-of-sight (LOS) channel. Consider the free space path loss model, the channel coefficient of A-UAV link $h_{au}[n]$ can be given by

$$h_{au}[n] = \frac{\beta_0}{x^2[n] + y^2[n] + h^2} = \beta_0 d_{au}^{-2}[n], \tag{3}$$

where β_0 denotes the reference channel coefficient at distance $d_0 = 1$ meter. $d_{au}[n] = \sqrt{x^2[n] + y^2[n] + h^2}$ denotes the distance between A and UAV at time slot n.

For the second phase the UAV normalizes its received signal by using the normalization factor δ, i.e., $x_u = \delta y_u$. The normalization factor δ can be expressed as

$$\delta = \sqrt{\frac{1}{p_a h_{au} + N_1}}. \tag{4}$$

Then UAV transmits the received signal to B with power p_u, the received signal at B can be written as

$$\begin{aligned} y_b[n] &= \sqrt{p_u[n]h_{ub}[n]}x_u[n] + z_2[n] \\ &= \delta\sqrt{p_u[n]h_{ub}[n]p_a[n]h_{au}[n]}x_a[n] \\ &\quad + \delta\sqrt{p_u[n]h_{ub}[n]}z_1[n] + z_2[n], \end{aligned} \tag{5}$$

where $x_u[n]$ is the transmitted data at UAV with circularly symmetric complex Gaussian distribution $CN(0, 1)$. $z_2[n]$ is the additive white Gaussian noise (AWGN) observed at B. Thus $z_2[n]$ follows $CN(0, N_2)$. $h_{ub}[n]$ denotes the channel coefficient of UAV-to-B link, which can be given by

$$h_{ub}[n] = \frac{\beta_0}{(x[n] - L)^2 + y^2[n] + h^2} = \beta_0 d_{ub}^{-2}[n], \tag{6}$$

where $d_{ub}[n] = \sqrt{(x[n] - L)^2 + y^2[n] + h^2}$ denotes the distance of UAV-to-B link at time slot n.

According to (4) and (5), the equivalent SNR at B $\gamma[n]$ can be written as

$$\gamma[n] = \frac{p_a[n]p_u[n]h_{au}[n]h_{ub}[n]}{p_a[n]h_{au}[n]N_2 + p_u[n]h_{ub}[n]N_1 + N_1N_2}. \tag{7}$$

The maximum transmission information rate for A-B link can be expressed as

$$R[n] = \frac{1}{2}\log_2(1 + \gamma[n]), \quad n = 1, \cdots, N. \tag{8}$$

III. THROUGHPUT MAXIMIZATION

In this paper, our main objective is to get the maximum throughput from source to destination during time period T by optimizing the source/relay power allocations $\{p_a[n], p_u[n]\}_{n=1}^{N}$, as well as the trajectory of UAV $\{x[n], y[n]\}_{n=1}^{N}$. The optimization problem can be summarized as

$$(\text{P1}): \max_{\substack{\{p_a[n],p_u[n]\}_{n=1}^{N} \\ \{x[n],y[n]\}_{n=1}^{N}}} \sum_{n=1}^{N} R[n], \tag{9}$$

$$\text{s.t.} \sum_{n=1}^{N} p_a[n] \leq N\bar{P}_a, \quad \sum_{n=1}^{N} p_u[n] \leq N\bar{P}_u, \tag{10}$$

$$p_a[n] \geq 0, \; p_u[n] \geq 0, \; n=1,\cdots,N, \tag{11}$$

$$\begin{aligned} &(x[n+1] - x[n])^2 \\ &+ (y[n+1] - y[n])^2 \leq \left(\frac{VT}{N}\right)^2, \\ &n = 1, 2, \cdots, N-1, \end{aligned} \tag{12}$$

where $\bar{P}_a$ and $\bar{P}_u$ represent the average maximum transmission power of A and UAV at each time slot, respectively.

(P1) is a non-convex optimization problem due to the objective function in (9) is non-convex. Therefore, (P1) is difficult to solve. In what follows, we develop iterative algorithms to efficiently solve (P1) by optimizing the source/relay power allocation with fixed trajectory and optimizing the UAV's trajectory with fixed power allocation alternately.

A. POWER ALLOCATION WITH FIXED TRAJECTORY

For any given UAV's trajectory $\{x[n], y[n]\}_{n=1}^{N}$, the source/relay power allocation problem can be written as the following problem (P1.1)

$$\text{(P1.1)}: \max_{\{p_a[n],p_u[n]\}_{n=1}^{N}} \sum_{n=1}^{N} R[n], \tag{13}$$
$$\text{s.t. (10) and (11).} \tag{14}$$

(P1.1) is still non-convex due to the objective function is non-convex. It is quite difficult to get the optimal solution. In what follows, we develop an iterative approximate solution based on successive convex optimization techniques. The main idea is to iteratively maximize the lower bound of achievable throughput by optimizing the source and UAV's transmission power iteratively. Let $\{p_{a,l}[n]\}_{n=1}^{N}$ and $\{p_{u,l}[n]\}_{n=1}^{N}$ be the transmission power of source and UAV at the lth iteration, $\{p_{a,l+1}[n]\}_{n=1}^{N}$ and $\{p_{u,l+1}[n]\}_{n=1}^{N}$ be the transmission power at the $(l+1)$th iteration. To obtain the iterative power allocation algorithm, we first show the following result.

Lemma 1: For any source and UAV's transmission power $\{p_{a,l+1}[n], p_{u,l+1}[n]\}_{n=1}^{N}$, the following inequality holds

$$R_{l+1}[n] \geq R_l[n] - \frac{\gamma_l^2[n]\log_2 e}{2(\gamma_l[n]+1)}\left(\frac{1}{\gamma_{l+1}[n]} - \frac{1}{\gamma_l[n]}\right) = R_{LB,l+1}, \quad n = 1, 2, \cdots, N. \tag{15}$$

Proof: To show Lemma 1, we first define the function $f(\alpha) = \log_2(1+\frac{1}{\alpha})$, which is a convex function with respect to $\alpha > 0$. The first-order Taylor approximation of a convex function is a global under-estimator, i.e., $f(\alpha) \geq f(\alpha_0)+\nabla f(\alpha_0)^T(\alpha-\alpha_0)$, where $\nabla f(\alpha_0)$ is the gradient of $f(\alpha)$ at α_0. Therefore, we have the following inequality

$$f(\alpha) \geq f_0(\alpha_0) - \frac{\log_2 e}{\alpha(\alpha+1)}(\alpha-\alpha_0) \tag{16}$$

By letting $\alpha \triangleq \frac{1}{\gamma_{l+1}[n]}$ and $\alpha_0 \triangleq \frac{1}{\gamma_l[n]}$, respectively, we have (15) follows from (16). ■

From Lemma 1 we can see that, at the nth time slot, for given transmission power $\{p_{a,l}[n], p_{u,l}[n]\}$ at the lth iteration and $\{p_{a,l+1}[n], p_{u,l+1}[n]\}$ at the $(l+1)$th iteration, the new resulting maximum information rate of A-to-B link is lower-bounded by $R_{LB,l+1}$. From (7) it is easy to verify that $1/\gamma[n]$ is a convex function with respect to $p_a[n]$ and $p_u[n]$. Therefore, the optimal solution of (P1.1) is lower-bounded by the following convex optimization problem (P1.2) for any given source and UAV transmission power $\{p_{a,l}[n], p_{u,l}[n]\}$,

$$\text{(P1.2)}: \max_{\{p_{a,l+1}[n],p_{u,l+1}[n]\}_{n=1}^{N}} \sum_{n=1}^{N} R_{LB,l+1}[n], \tag{17}$$
$$\text{s.t.} \sum_{n=1}^{N} p_{a,l+1}[n] \leq N\bar{P}_a,$$
$$\sum_{n=1}^{N} p_{u,l+1}[n] \leq N\bar{P}_u, \tag{18}$$
$$p_{a,l+1}[n] \geq 0,$$
$$p_{u,l+1}[n] \geq 0, n = 1, \cdots, N. \tag{19}$$

(P1.2) is a convex optimization problem, which can be efficiently solved by standard convex optimization techniques such as interior-point method [21]. Thus (P1.1) can be iteratively approximated by solving (P1.2) at each iteration, as shown in Algorithm 1.

Algorithm 1 Source/UAV Power Allocation With Given UAV Trajectory

1: Let $l = 0$ and initialize source and UAV's transmission power $\{p_{a,l}[n], p_{u,l}[n]\}_{n=1}^{N}$.
2: **repeat**
3: Solve (P1.2) by standard convex optimization techniques to obtain the new source and UAV's transmission power $\{p_{a,l+1}[n], p_{u,l+1}[n]\}_{n=1}^{N}$.
4: Update $l = l+1$.
5: **until** converge or the preset number of iterations has been reached.
6: Output $\{p_a[n], p_u[n]\}_{n=1}^{N}$.

B. TRAJECTORY OPTIMIZATION WITH FIXED POWER ALLOCATION

For any given source/relay power allocation scheme $\{p_a[n], p_u[n]\}_{n=1}^{N}$, the trajectory optimization problem can be written as the following problem (P1.3)

$$\text{(P1.3)}: \max_{\{x[n],y[n]\}_{n=1}^{N}} \sum_{n=1}^{N} R[n], \tag{20}$$
$$\text{s.t. (12).} \tag{21}$$

The objective function of (P1.3) is not convex with respect to $\{x[n], y[n],\}_{n=1}^{N}$. In this subsection, we develop an iterative algorithm to optimize the lower bound of overall throughput by successive convex optimization techniques. Let $\{x_l[n], y_l[n]\}_{n=1}^{N}$ be the location of UAV at each time slot in the lth iteration, $\{x_{l+1}[n], y_{l+1}[n]\}_{n=1}^{N}$ be the location of UAV at each time slot in the $(l+1)$th iteration. To obtain the iterative power allocation algorithm, we first show the following result.

Lemma 2: Let $\lambda_1[n] = 1/h_{au}[n]$, $\lambda_2[n] = 1/h_{ub}[n]$, respectively. For any UAV's trajectory $\{x_{l+1}[n], y_{l+1}[n]\}_{n=1}^{N}$ at $l+1$th iteration, the following inequality with respect to the equivalent SNR holds

$$\gamma_{l+1}[n] \geq \gamma_l[n] - D_{1,l}[n]\left(\lambda_{1,l+1}[n] - \lambda_{1,l}[n]\right) - D_{2,l}[n]\left(\lambda_{2,l+1}[n] - \lambda_{2,l}[n]\right) = \gamma_{LB,l}[n], \quad n = 1, 2, \cdots, N, \tag{22}$$

where

$$D_{1,l}[n] = \frac{p_a[n]p_u[n](p_u[n]N_1+N_1N_2\lambda_{2,l}[n])}{\left(p_a[n]N_2\lambda_{2,l}[n] + p_u[n]N_1\lambda_{1,l}[n]+N_1N_2\lambda_{1,l}[n]\lambda_{2,l}[n]\right)^2} > 0, \tag{23}$$

$$D_{2,l}[n] = \frac{p_a[n]p_u[n](p_a[n]N_2+N_1N_2\lambda_{1,l}[n])}{\left(p_a[n]N_2\lambda_{2,l}[n]+p_u[n]N_1\lambda_{1,l}[n]+N_1N_2\lambda_{1,l}[n]\lambda_{2,l}[n]\right)^2} > 0. \quad (24)$$

Proof: From (7) the equivalent SNR at the nth time slot can be written as

$$\gamma[n] = \frac{p_a[n]p_u[n]}{p_a[n]N_2\lambda_2[n]+p_u[n]N_1\lambda_1[n]+N_1N_2\lambda_1[n]\lambda_2[n]}. \quad (25)$$

It is easy to verify that $\gamma[n]$ is a convex function with respect to $\lambda_1[n]$ and $\lambda_2[n]$, though it is not convex with respect to $x[n]$ and $y[n]$. It is known that the first-order Taylor series expansion of a convex function provides a lower bound, i.e., $f(\alpha) \geq f(\alpha_0) + \nabla f(\alpha_0)^T(\alpha - \alpha_0)$.

Therefore, $\gamma_{l+1}[n]$ is lower bounded by its first-order Taylor approximation at $(\lambda_{1,l}[n], \lambda_{2,l}[n])$ as shown in Lemma 2. ■

Since $R[n]$ is a monotonically increasing function with respect to $\gamma[n]$, $R[n]$ is lower bounded by $\frac{1}{2}\log 2(1+\gamma_{LB}[n])$. Though $\gamma[n]$ is not concave with respect to $x[n]$ and $y[n]$, it can be easily verified that $\gamma_{LB}[n]$ is concave with respect to $x[n]$ and $y[n]$. From Lemma 2 we can conclude that for given source and UAV's power allocation scheme $\{p_a[n], p_u[n]\}_{n=1}^N$, the overall throughput of this system is lower bounded by the optimal solution of the following convex optimization problem (P1.4)

$$\text{(P1.4)}: \max_{\{x_{l+1}[n], y_{l+1}[n]\}_{n=1}^N} \sum_{n=1}^{N} \log_2\left(1+\gamma_{LB,l}[n]\right), \quad (26)$$

$$\text{s.t. } (x_{l+1}[n+1]-x_{l+1}[n])^2 + (y_{l+1}[n+1]-y_{l+1}[n])^2 \leq \left(\frac{VT}{N}\right)^2, \quad n = 1, 2, \cdots, N-1. \quad (27)$$

(P1.4) is a convex optimization problem, which can be efficiently solved. Therefore the solution of (P1.3) can be iteratively approximated by successively solving (P1.4), the algorithm is summarized in Algorithm 2.

Algorithm 2 Trajectory Optimization With Given Power Allocation

1: Let $l = 0$ and initialize the UAV's trajectory $\{x_l[n], y_l[n]\}_{n=1}^N$.
2: **repeat**
3: Solve (P1.4) by standard convex optimization techniques to obtain the new UAV's trajectory $\{x_{l+1}[n], y_{l+1}[n]\}_{n=1}^N$.
4: Update $l = l + 1$.
5: **until** converge or the preset number of iterations has been reached.
6: Output $\{x[n], y[n]\}_{n=1}^N$.

C. ITERATIVE POWER AND TRAJECTORY OPTIMIZATION

Based on the solutions obtained in algorithm 1 and algorithm 2, Problem (P1) can be iteratively solved, by optimizing the source/UAV power allocation problem with given UAV trajectory and trajectory optimization problem with given source/UAV power allocation scheme alternately. The associated algorithm is summarized in Algorithm 3. We have the following result.

Algorithm 3 Iterative Power and Trajectory Optimization Algorithm

1: Initialize the UAV's trajectory.
2: **repeat**
3: For given UAV trajectory, update source/UAV power allocation scheme by Algorithm 1.
4: For given source/UAV power allocation scheme, update the UAV's trajectory by Algorithm 2.
5: **until** converge or the preset number of iterations has been reached.
6: Output $\{p_a[n], p_u[n]\}_{n=1}^N$ and $\{x[n], y[n]\}_{n=1}^N$.

Theorem 1: The results of Algorithm 3 lead to a lower bound of the maximum throughput. Furthermore, algorithm 3 is guaranteed to converge.

Proof: Note that results of both Algorithm 1 and Algorithm 2 are the lower bound of the maximum throughput, Algorithm 3 employ Algorithm 1 and Algorithm 2 alternately. Therefore, results of Algorithm 3 lead to a lower bound of the maximum throughput.

Let C_1, C_2 and C_3 be the throughput obtained by Algorithm 1, 2, and 3, respectively. Based on Lemma 1 and Lemma 2, it is easy to verify that $C_{1,l+1} \geq C_{1,l}$ at $(l+1)$th iteration of Algorithm 1 and $C_{2,l+1} \geq C_{2,l}$ at $(l+1)$th iteration of Algorithm 2, respectively, i.e., both the resulting optimal values of (P1.2) and (P1.4) are nondecreasing over the iteration l. Therefore, we can conclude that $C_{3,i+1} \geq C_{3,i+1}$ at $(i+1)$th iteration of Algorithm 3, i.e., the resulting throughput of Algorithm 3 is nondecreasing over iteration i. Whereas C_3 in Algorithm 3 is upper-bounded by the optimal solution of (P1). Thus Algorithm 3 is guaranteed to converge. ■

Note that Algorithm 3 only requires solving convex optimization problems at each iteration, the overall complexity of Algorithm 3 is polynomial in the worst situation. However, Algorithm 3 does not converge to the optimal solution. Since Algorithm 1 and Algorithm 2 are lower bounds of the maximum throughput, respectively, which are not guaranteed to be optimal.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, numerical results are demonstrated to show the performance of our proposed power allocation and trajectory optimization schemes. We consider a mobile relay system that the distance between A and B is $L = 2000$m, i.e. the coordinates of A and B are (0, 0, 0) and

(2000, 0, 0), respectively. The altitude of UAV is fixed at $h = 100$m. The communication links between UAV and ground nodes are at a carrier frequency of $f_c = 5$GHz with bandwidth $B_0 = 20$Mhz. Without loss of generality, we assume the noise power spectrum density at UAV and B are equal, i.e. $N_0 = N_1 = N_2$, and the value is $N_0 = -169$dBm/Hz. Therefore, the reference SNR at $d_0 = 1$m with 0dBm transmit power can be obtained as $\beta_0/(B_0 N_0) \approx 50$dB. The maximum flying speed of UAV is $V = 50$m/s. In this section, we consider the scenario that the initial and final locations of the mobile relay are pre-determined. This is because in practice, the initial and final relay locations depend on various factors such as the UAV's launching/landing locations as well as its pre-mission and post-mission flying paths, etc. We assume that the UAV flies from $(x[1], y[1], h) = (0, 0, 100)$ to $(x[N], y[N], h) = (2000, 0, 100)$ in 100 seconds.

A. POWER ALLOCATION WITH FIXED UAV TRAJECTORY

Firstly, we show the power allocation results obtained by Algorithm 1 with fixed UAV trajectory. The UAV flies directly from $(x[1], y[1], h) = (0, 0, 100)$ to $(x[N], y[N], h) = (2000, 0, 100)$ in 100 seconds. The flying speed of UAV is a constant at 20m/s. We assume that the source node A and the UAV has the same average transmission power, i.e. $\bar{p} = \bar{p}_a = \bar{p}_u$. Fig. 2(a) and Fig. 2(b) show the power allocation results with different average transmission power $\bar{p}$. In Fig. 2(a) the average transmission power is $\bar{p} = 0$dBm. We can see that when the UAV is close to A, the UAV works with high transmission power, whereas the transmission power of source node A is relatively low. From 20s to 80s, we can observe that the transmission power of A and UAV is zero. This implies that there is no data transmission in this time period. When UAV flies near node B, the UAV transmits with low power, whereas A works with high transmission power. This is because when UAV is close to A, UAV should transmit with higher power to ferry the received information from A due to the longer link distance, and vice versa. From (7) we can find that when the power budget of A and UAV is small, the equivalent SNR reaches maximum when UAV is close to A or B. Therefore, all the power is allocated when UAV is close A or B to maximize the overall throughput, and there is no transmission in the middle of UAV trajectory. In Fig. 2(b) the average transmission power is $\bar{p} = 20$dBm. We can see that the transmission power of A increases whereas the transmission power of UAV decreases as the UAV flies form from (0, 0, 100) to (2000, 0, 100). This is because more transmission power is needed when the link distance is longer due to the higher path loss.

B. UAV TRAJECTORY OPTIMIZATION WITH FIXED POWER ALLOCATION

Then we consider the situation that the transmission power of source node A and UAV are fixed, whereas the UAV trajectory is optimized to maximize the end-to-end throughput by Algorithm 2. The source node A and the UAV has the same constant transmission power $p_a = p_u$ in a time horizon of 100 seconds. Fig. 3(a) and Fig. 3(b) show the optimized UAV trajectories with different transmission power $\bar{p}$. The UAV flies at a fixed altitude $h = 100$m. Thus only the x

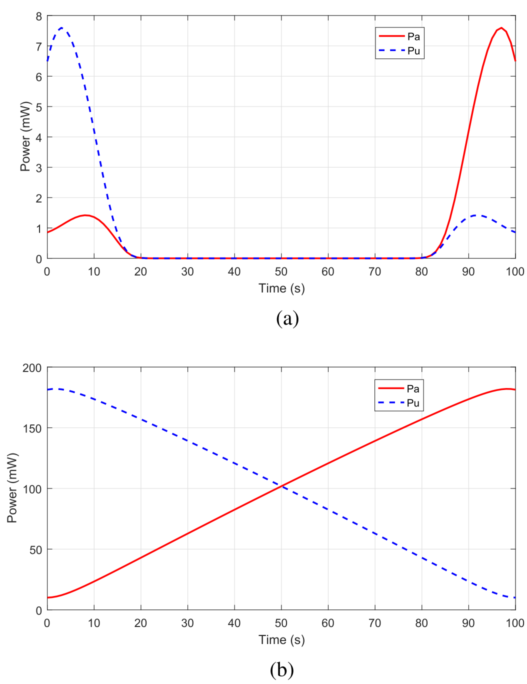

FIGURE 2. **Power allocation results by Algorithm 1. (a)$\bar{P}_a = \bar{P}_u = 0$dBm. (b) $\bar{P}_a = \bar{P}_u = 20$dBm.**

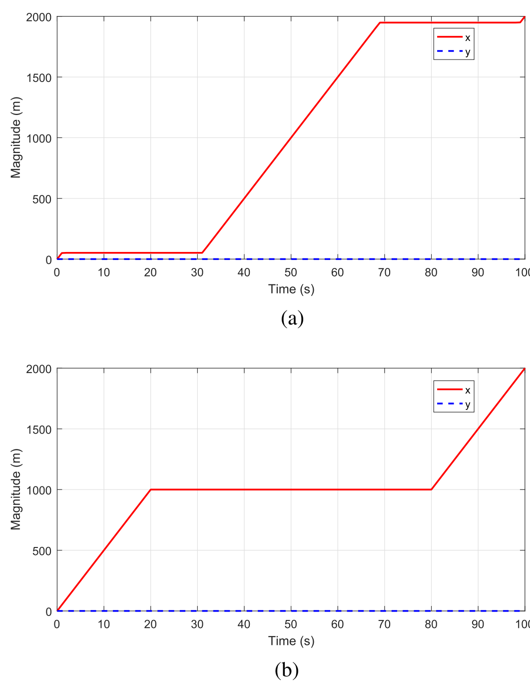

FIGURE 3. **Trajectory optimization results by Algorithm 2. (a) $p_a = p_u = 0$dBm. (b) $p_a = p_u = 20$dBm.**

axis and y axis of the UAV coordinates are plotted. Form Fig. 3(a) and Fig. 3(b) we can see that the optimal value of y axis is always zero. This is because the link distance reaches minimum when value of y axis is zero, which leads to the minimum path loss. Fig. 3(a) illustrates the UAV trajectory with constant transmission power $p_a = p_u =$ 0dBm. It is shown that the UAV flies with its maximum speed to the position of (51.6, 0, 100), and hovers for a time horizon of 30 seconds. Then the UAV flies with its maximum speed towards (1948.4, 0, 100) and hovers for another 30 seconds. Finally the UAV flies to the destination with its maximum speed. This is because with constant transmission power of 0dBm, the achievable information rate in (8) reaches maximum at (51.6, 0, 100) and (1948.4, 0, 100). Therefore, the UAV hovers at these two positions as long as it can to maximize the throughput. In Fig. 3(b), node A and UAV work with constant transmission power $p_a = p_u =$ 20dBm. In this case the UAV flies with its maximum speed to the position (1000, 0, 100) and hovers for a time horizon of 60 seconds. Then it flies to the destination with the maximum speed. This is because with constant transmission power of 20dBm, the achievable information rate in (8) reaches maximum at the position (1000, 0, 100). In the proposed UAV trajectory optimization scheme, the UAV always choose to hover at the best position as long as possible to achieve the maximum throughput.

C. JONIT TRANSMISSION POWER AND TRAJECTORY OPTIMIZATION

Lastly, we consider the situation that the transmission power of node A and the UAV, as well as the UAV trajectory are optimized to maximize the throughput by Algorithm 3. The results of optimized transmission power and UAV trajectory with different average transmission power budget are illustrated in Fig. 4. The optimized power and trajectory with average transmission power $\bar{p} =$ 0dBm are shown in Fig. 4(a) and Fig. 4(b), respectively. In this case, we can easily see that the UAV flies to the position (44, 0, 100) and hovers for a time horizon of 12 seconds. Then it flies and reaches the position (1956, 0, 100) at the time instant 87s. It hovers at (1956, 0, 100) for another 12 seconds before flying to the destination. Besides, almost all the information is transmitted when the UAV hovers at (44, 0, 100) and (1956, 0, 100). At (44, 0, 100) the UAV works with higher transmission power compared to A due to its longer link distance. At (1956, 0, 100) the transmission power of A is higher. This is because the achievable information rate obtained by (8) reaches maximum at (44, 0, 100) and (1956, 0, 100) in Algorithm 3, and more power should be allocated to the link with longer distance. The optimized power and trajectory with average transmission power $\bar{p} =$ 20dBm are shown in Fig. 4(c) and Fig. 4(d), respectively. we can observe that the UAV flies with its maximum speed to the position (1000, 0, 100) and hovers for a time horizon of 60 seconds. Then it flies to the destination with the maximum speed. From 0s to 20s, the transmission power of A increases to 20dBm, whereas the transmission power of UAV decreases to 20dBm due to the difference link distances. From 20s to 80s, the source node A and UAV transmit with equal power 20dBm with equal link distance. From 80s to 100s, the transmission power of A increases, whereas the transmission power of UAV decreases due to the differences in link distances.

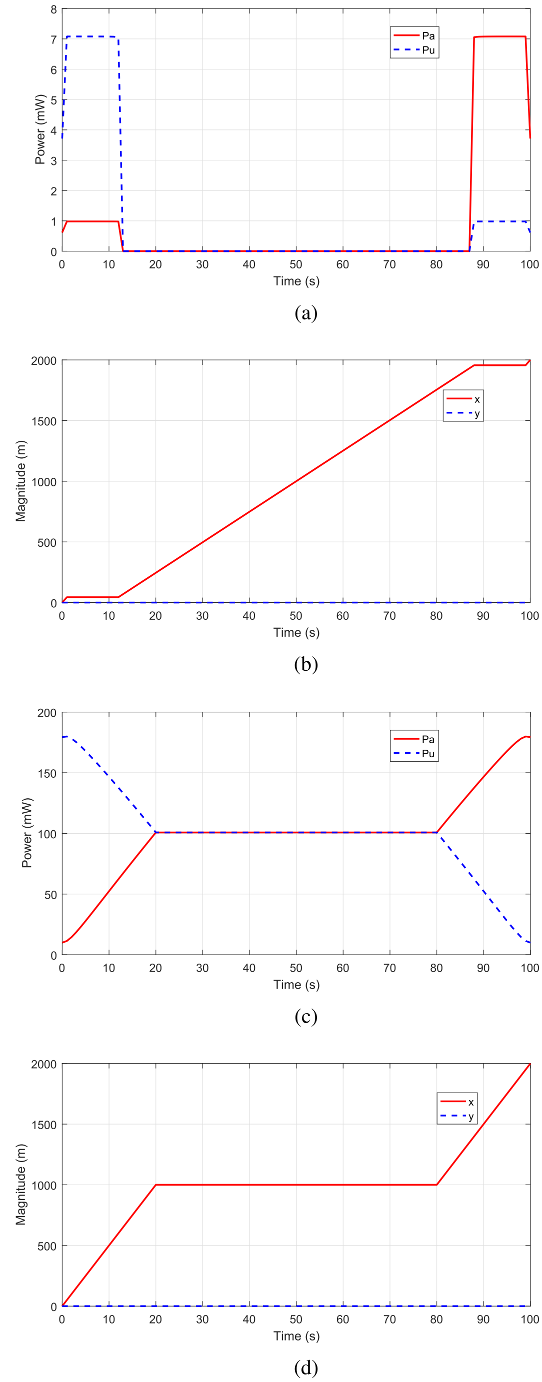

FIGURE 4. Joint Power and trajectory optimization results by Algorithm 3. (a) Power allocation with $\bar{P}_a = \bar{P}_u =$ 0dBm. (b) Trajectory optimization with $\bar{P}_a = \bar{P}_u =$ 0dBm. (c) Power allocation with $\bar{P}_a = \bar{P}_u =$ 20dBm. (d) Trajectory optimization with $\bar{P}_a = \bar{P}_u =$ 20dBm.

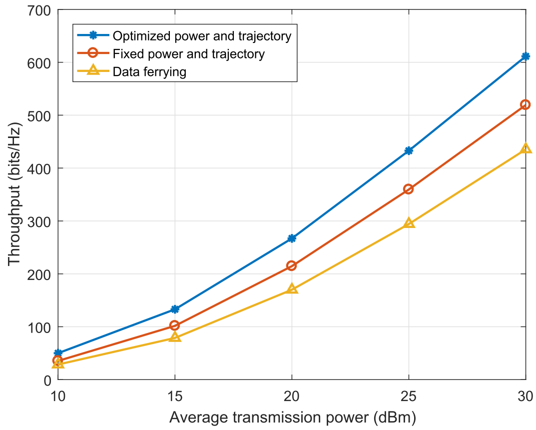

FIGURE 5. Throughput with various power and trajectory strategies.

Further, the throughput of the joint transmission power and UAV trajectory optimization is evaluated. The case of fixed power and trajectory is employed as a benchmark, i.e., the source node A and the UAV has the same constant transmission power $p_a = p_u$ in a time horizon of 100 seconds, and the UAV flies directly from $(x[1], y[1], h) = (0, 0, 100)$ to $(x[N], y[N], h) = (2000, 0, 100)$ in 100 seconds with constant speed 20m/s. Besides, another benchmark scheme called *data ferrying* [22], is also employed. Where the UAV first hovers above source node A and transmits data for a period of time, then flies with its maximum speed towards destination node B to hover and transmit data for another time period. In Fig. 5, the throughput achieved by different schemes versus different average transmission power $\bar{p} = \bar{p}_a = \bar{p}_u$ is plotted. From Fig. 5, we can see that compared to the fixed power and trajectory scheme, significant improvement of throughput can be achieved by the proposed joint transmission power and UAV trajectory algorithm. Besides, the data ferrying scheme is even worse than the fixed power and trajectory scheme. This is because the data ferrying scheme is designed for delay-tolerant decode-and-forward (DF) application, which has higher throughput at the cost of much higher end-to-end delay compared to the amplify-and-forward (AF) scheme employed in this paper. In this paper, we consider the realtime communication situation, i.e., as soon as the UAV received data from source node, it transmits the data to the destination immediately. Therefore, the proposed joint power and trajectory scheme is much better than data ferrying scheme in this scenario.

V. CONCLUSION

This paper studies a UAV based mobile relay system to connect two isolated ground nodes. The AF relay strategy is employed to reduce the delay and the device complexity. The source/relay transmission power and the UAV trajectory are optimized to achieve to maximum end-to-end throughput of this AF relay system. For the fixed UAV trajectory situation, we develop an iterative algorithm to obtain a lower bound of the maximum throughput by optimizing the source/relay power allocation. For the fixed source/relay transmission power situation, another iterative algorithm to achieve the lower bound of the maximum throughput by UAV trajectory optimization. Based on the above results, an iterative algorithm is proposed to jointly optimize the power allocation and relay trajectory in an alternate manner. Numerical results show that compared to the fixed power and trajectory scheme, significant improvement of throughput can be achieved by the proposed power and trajectory optimization scheme.

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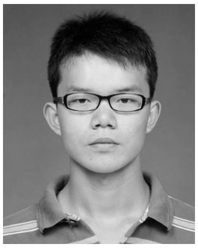

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