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Joint Trajectory and Power Optimization for UAV Relay Networks

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***Abstract*— In this letter, we consider an unmanned aerial vehicle (UAV) relay network, where the UAV works as an amplify-and-forward relay. We optimize the trajectory of UAV, the transmit power of UAV, and the mobile device by minimizing the outage probability of this relay network. The analytical expression of outage probability is derived first. A closed-form low-complexity solution with joint trajectory design and power control is proposed to solve this non-convex problem. Simulation results show that the outage probability of the proposed solution is significantly lower than that of the fixed power relay and circle trajectory for the UAV relay.**

***Index Terms*— UAV relaying, outage probability, power control, trajectory design.**

I. Introduction

The unmanned aerial vehicle (UAV) is an emerging technique in military, public and civil applications [1]. The attractive advantages of UAV for networked communications include high mobility, flexible deployment, and low operational costs. Recently, UAVs become especially helpful in the situations with widely scattered users, large obstacles such as hills or buildings that deteriorates the quality of links, and communication disabilities due to natural disasters [2].

Wireless communication with the assist of UAV, i.e., UAV relay, has been widely discussed. In UAV-aided relay networks, UAVs are deployed to provide wireless connectivities between two or more distant users or user groups without reliable direct communication links [5]. In [4], an energy efficiency maximization algorithm is proposed for UAV relay with circular trajectory. Zeng *et al.* [5] study throughput maximization of a rectilinear trajectory UAV relay network. However, most of the works only consider the location of UAV as a fixed point or on a fixed trajectory. In practice, UAVs can move freely in the 3-dimensional space to achieve a better performance, but the trajectory design and power control on this condition have not been well studied.

In this letter, we consider a half-duplex uplink UAV relay network with a UAV, a base station (BS), and a mobile device (MD). The UAV works as an amplify-and-forward (AF) relay, which is capable to adjust its transmit power and flying trajectory. We formulate the trajectory design and power control as a non-convex outage probability minimization problem. The problem is decoupled into trajectory design and power control subproblems. For these two subproblems, we address them by gradient descent method and extremum principles, respectively. Finally, an approximate solution of trajectory design and power control is obtained to approach the minimum outage probability.

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amplification coefficient: Gt

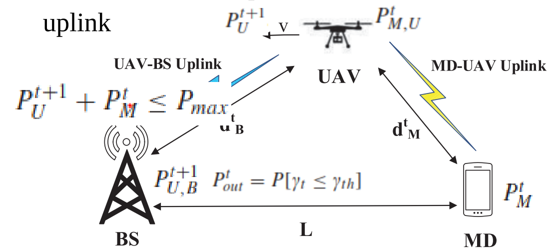

Fig. 1. System model for communication with UAV relay.

II. System Model and Problem Formulation

As shown in Fig. 1, we consider an uplink scenario in a cellular network with one BS and one MD which is beyond the coverage of BS. A UAV works as an AF relay to provide communication service for the MD. During the transmission, the UAV adjusts its location to improve the service quality. We assume that the transmission process contains N time slots. In two consecutive time slots, the MD transmits signals to UAV in the first time slot, and the UAV amplifies and forwards the received signals from the MD to BS in the second time slot. We denote the locations of BS and MD by B and M.

Let L be the distance between the BS and MD. In time slot t, the distance between MD and UAV and the distance between UAV and BS are given by d_M^t and d_B^t, respectively. The flying distance of UAV from time slot i to time slot j is $d_{i,j}$. We assume that the UAV can fly for a maximum distance of υ in each time slot, where $\upsilon \ll L$. The transmit power of MD in time slot t is given by P_M^t, and the transmit power of UAV in time slot $(t+1)$ is given by P_U^{t+1}. The total transmit power in time slot t and $(t+1)$ is constrained,[1] i.e., $P_M^t + P_U^{t+1} \le P_{max}$.

In time slot t, the received power at UAV from the MD is expressed as [7]

$$P_{M,U}^t = P_M^t (d_M^t)^{-\alpha} \| h_M^t \|^2. \tag{1}$$

In time slot $(t+1)$, the received power at BS is shown as

$$P_{U,B}^{t+1} = P_U^{t+1} (d_B^{t+1})^{-\alpha} \| h_B^{t+1} \|^2, \tag{2}$$

where α is the path loss exponent, and h_M^t, h_B^{t+1} are independent small-scale channel fading coefficients with zero mean and unit variance. The noise at each node satisfies the Gaussian

[1] With total power constraint, the maximum power efficiency can be reached with different transmission distances scenarios [6].

distribution with zero mean and N_0 as variance. The received signal of UAV relay is expressed as

$$Y_{UAV}^t = \sqrt{P_M^t (d_M^t)^{-\alpha}} h_M^t X_M^t + n_U^t, \tag{3}$$

where X_M^t is the signal of unit energy from the MD, and n_U^t is the noise received at the UAV relay. The amplification coefficient of the UAV relay is given by

$$G_t = \sqrt{P_U^{t+1} / \left(P_M^t (d_M^t)^{-\alpha} \|h_M^t\|^2 + N_0\right)}. \tag{4}$$

After being amplified by the UAV relay, the received signal at BS can be expressed as

$$\begin{aligned} Y_{BS}^{t+1} = G_t \sqrt{P_M^t (d_M^t)^{-\alpha} (d_B^{t+1})^{-\alpha}} h_M^t h_B^{t+1} X_M^t \\ + n_U^t G_t \sqrt{(d_B^{t+1})^{-\alpha}} h_B^{t+1} + n_B^{t+1}, \end{aligned} \tag{5}$$

where n_B^{t+1} is the noise received at BS. According to (5), the signal-to-noise ratio (SNR) of the network is given by

$$\gamma_t = \frac{P_M^t (d_M^t)^{-\alpha} \|h_M^t\|^2 G_t^2 (d_B^{t+1})^{-\alpha} \|h_B^{t+1}\|^2}{N_0 G_t^2 (d_B^{t+1})^{-\alpha} \|h_B^{t+1}\|^2 + N_0}. \tag{6}$$

The outage probability is defined as the probability that the SNR falls below a predetermined threshold γ_{th}. Thus, the outage probability of the uplink can be derived by integrating the probability density function (PDF) of γ_t, shown as

$$\boxed{P_{out}^t = P[\gamma_t \leq \gamma_{th}]} = \int_0^{\gamma_{th}} f(\gamma_t) d\gamma_t. \tag{7}$$

Theorem 1: The approximate solution of the outage probability in time slot t and $(t+1)$ is

$$\begin{aligned} P_{out}^t &= 1 - \exp\left(-\frac{N_0 \gamma_{th}}{P_M^t (d_M^t)^{-\alpha}}\right) \times (1 + 2V^2 \ln V), \\ V &= \sqrt{(N_0 \gamma_{th}) / (P_U^{t+1} (d_B^{t+1})^{-\alpha})}. \end{aligned} \tag{8}$$

Proof: See Appendix A. □

Our objective is to minimize the outage probability by optimizing both the UAV trajectory and the power of UAV and MD. The expression of (8) shows that the outage probability in time slot t is only affected by the power and location parameters in time slot t and $(t+1)$. Therefore, we simplify the optimization objective as the outage probability in a single time slot, and the problem can be formulated by:

$$\min_{P_M^t, P_U^{t+1}, d_M^t, d_B^{t+1}} \; P_{out}^t, \tag{9a}$$

$$\text{s.t.} \; P_U^{t+1} + P_M^t \leq P_{max}, \tag{9b}$$

$$P_U^{t+1} \geq 0, \quad P_M^t \geq 0, \tag{9c}$$

$$d_{t,t+1} \leq \upsilon, \tag{9d}$$

where (9b) and (9c) are the power constraints for UAV and MD, and (9d) shows the UAV mobility constraint.

III. Power and Trajectory Optimization

The expression of (8) shows that the joint power and trajectory optimization problem (9) is non-convex. In this section, we tackle the problem through alternating minimization, where trajectory design and power control are optimized iteratively.

The algorithm is illustrated in Algorithm 1. In each iteration, we design the trajectory given the power control results obtained by the last iteration, and then solve the power control subproblem given the UAV trajectory. In iteration k, let $S^k = \sum_{t=1}^{N} P_{out}^t$, the algorithm converges when $S^k - S^{k-1} < \epsilon$, where ϵ is a predefined error tolerance threshold.

Algorithm 1 Power and Trajectory Optimization Algorithm

1: **Initialize** $k = 0$, $S^0 = 0$, $P_M^t = P_U^{t+1} = P_{max}/2$, $\forall t = 1, 3, \cdots, N$;
2: **Repeat**
3: $k = k + 1$;
4: **For** $t = 1 : N$
5: Solve trajectory design subproblem (10) for slot t;
6: **For** $t = 1 : N$
7: Solve power control subproblem (12) for slot t;
8: **Until** $S^k - S^{k-1} \leq \epsilon$

A. Trajectory Design

Given the power control variables P_M^t and P_U^{t+1}, (9) can be expressed as

$$\min_{d_M^t, d_B^{t+1}} \; P_{out}^t, \tag{10a}$$

$$\text{s.t.} \; d_{t,t+1} \leq \upsilon. \tag{10b}$$

Problem (10) is also non-convex. To achieve a local minimum outage probability, the UAV will fly in the direction with the maximum outage probability descent velocity, i.e., $-\nabla P_{out}^t$. Let $(0,0,0)$ and $(L,0,0)$ be the locations of the BS and the MD, respectively. In time slot t, we denote the location of UAV by $\boldsymbol{l_t} = (x_t, y_t, z_t)$, and the trajectory by $\boldsymbol{\Delta l_t} = (\Delta x_t, \Delta y_t, \Delta z_t)$, with $|\boldsymbol{\Delta l_t}| \ll |\boldsymbol{l_t}|$. When the high-order terms are neglected, the trajectory direction of the UAV, i.e., the gradient of the outage probability function is expressed as

$$\begin{aligned} -\nabla P_{out}^t = ((R - M)x_t + ML)\hat{\boldsymbol{i}} + (R - M)y_t \hat{\boldsymbol{j}} \\ + (R - M)z_t \hat{\boldsymbol{k}}, \end{aligned} \tag{11}$$

where $M = \frac{N_0 \gamma_{th}}{P_M^t} \left((x_t - L)^2 + y_t^2 + z_t^2\right)^{\alpha/2-1} (1 + Q \ln Q)$, $R = \frac{N_0 \gamma_{th}}{P_U^{t+1}} (x_t^2 + y_t^2 + z_t^2)^{\alpha/2-1} (1 + \ln Q)$, and $Q = \frac{N_0 \gamma_{th}}{P_U^{t+1}} (x_t^2 + y_t^2 + z_t^2)^{\alpha/2}$; $\hat{\boldsymbol{i}}$, $\hat{\boldsymbol{j}}$, and $\hat{\boldsymbol{k}}$ are the unit vectors of x, y, and z axis.

Since $\upsilon \ll L$, we set the step size of the gradient descent process as υ for each time slot. We also set a minimum outage probability threshold δ, with $\delta \to 0^-$. When $-\nabla P_{out}^t \geq \delta$, it is regarded that the minimum outage probability is achieved, and the UAV stops moving. In the trajectory design for time slot $(t+1)$, the location of UAV is updated as $\boldsymbol{l_{t+1}} = \boldsymbol{l_t} + \boldsymbol{\Delta l_t}$.

Theorem 2: When the outage probability is minimized, BS, MD, and UAV are collinear, and $d_B^t < d_M^t$ is satisfied.

Proof: See Appendix B. □

B. Power Control

Given the UAV trajectory $\boldsymbol{l_t}$, (9) can be rewritten as

$$\min_{P_M^t, P_U^{t+1}} \; P_{out}^t, \tag{12a}$$

$$\text{s.t.} \; P_U^{t+1} + P_M^t \leq P_{max}, \tag{12b}$$

$$P_U^{t+1} \geq 0, \; P_M^t \geq 0. \tag{12c}$$

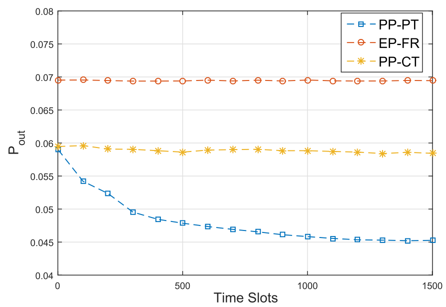

Fig. 2. Time slot vs. Outage probability.

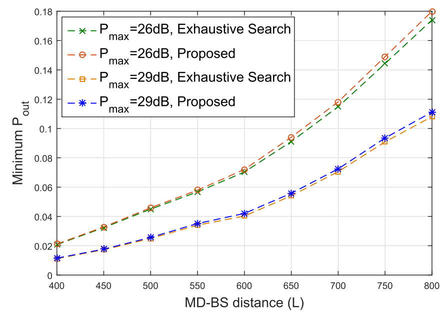

Fig. 3. MD-BS distance (L) vs. Minimum outage probability.

Theorem 3: The minimized outage probability is obtained when $P_U^{t+1} + P_M^t = P_{max}$ is satisfied.

Proof: See Appendix C. □

We substitute $P_M^t = P_{max} - P_U^{t+1}$ into (12), and P_{out}^t is a function of P_U^{t+1}. The outage probability function in (12) is convex with respect to P_U^{t+1}. Therefore, when $\frac{d(P_{out})}{d P_U^{t+1}} = 0$, the optimal power control is realized. The closed-form solution of power control is given in Appendix C.

Theorem 4: The proposed power control is mostly determined by d_M^t / d_B^{t+1}. When $d_M^t \ll d_B^{t+1}$ or $d_M^t \gg d_B^{t+1}$, $P_U^{t+1} \to 0$, and the transmit power of MD is $P_M^t \to P_{max}$.

Proof: See Appendix D. □

IV. Simulation Results

In this section, we evaluate the performance of Algorithm 1. The selection of the simulation parameters is based on the existing works and 3GPP specifications [9], [10]. We consider $N = 1500$ time slots, and the distance between the MD and BS $L = 500$. The maximum initial MD-UAV and UAV-BS distances (d_M^1 and d_U^1) are set as $\frac{3}{5}L$. We set the maximum moving distance for UAV in each time slot as $\upsilon = 0.1$, and also set $\delta = -10^{-2}$, $\epsilon = -10^{-2}$. The maximum total transmit power P_{max} is given as 26 dBm, and the noise variance N_0 is given as -96 dBm. The SNR threshold γ_{th} is 0 dB, and the path loss exponent α is 4.

We provide two schemes in comparison with the proposed power control and trajectory design scheme (PP-PT): proposed power control with circle trajectory scheme (PP-CT), and equal power allocation with fixed relay scheme (EP-FR). In PP-CT, the trajectory is a circle whose center is $(L/2, 0, 0)$ and radium is 100. The initial location of UAV is a random point on this circle and the moving distance is υ for a time slot. The power control is the same as our proposed algorithm. In EP-FR, the location of UAV is fixed in different time slots, which obeys uniform distribution in a circle area with $(L/2, 0, 0)$ being the center, and $L/2$ being the radium. The MD and UAV use the same transmit power in different time slots.

Fig. 2 depicts the average outage probability with time axis. The outage probability obtained by PP-PT decreases with time at the beginning. After about 1000 time slots, the outage probability decreases about 23% and turns stable at the minimum level, which is consistent with Remark 1. The average outage probability of PP-CT scheme is similar with PP-PT at the beginning, but it does not decrease with time since the trajectory is fixed. The outage probability obtained by EP-FR is about 18% higher than the scheme with PP-CT.

Fig. 3 illustrates the distance between the MD and BS versus the minimum achievable outage probability. The number of transmission time slots N is sufficiently large for the UAV to achieve the minimum outage probability with our proposed solution. The minimum outage probability of exhaustive search is obtained by enumerating the outage probability of over 1000 power control strategies and over 5000 UAV location possibilities. It is shown that the minimum outage probability increases monotonically with the increment of L. When the maximum total transmit power is raised from 26 dBm to 29 dBm, the outage probability will decrease about 40%. The difference between the minimum outage probability obtained by the proposed solution and exhaustive search is less than 5% in all of our simulations.

V. Conclusions

In this letter, we consider an uplink network model with a UAV working as an AF relay. An analytical expression of the outage probability is derived. With power and UAV speed constraints, we give a joint solution for the trajectory design and power control. The outage probability of proposed solution outperforms fixed power and circle trajectory schemes significantly, and is close to the exhaustive search minimum outage probability, with a difference less than 5%.

Appendix A
Proof of Theorem 1

Proof: According to (6), we rewrite SNR γ_t as

$$\gamma_t = \left(a P_{M,U}^t P_{U,B}^{t+1}\right) / \left(a P_{U,B}^{t+1} N_0 + N_0\right), \tag{13}$$

where $a = G_t^2 / P_U^{t+1}$. Variables $P_{M,U}^t$ and $P_{U,B}^{t+1}$ obey exponential distribution for their physical significance. The outage probability in (7) can be simplified as

$$P_{out}^t = P(P_{M,U}^t \leq S + W), \tag{14}$$

where $S = N_0 \gamma_{th}$ and $W = N_0 \gamma_{th} / a P_{U,B}^{t+1}$. Let $\Phi = P_M^t (d_M^t)^{-\alpha}$, the outage probability can be rewritten by

$$\begin{aligned} P_{out}^t &= E_{S+W}\{P(P_{M,U}^t \leq s + w | s + w)\} \\ &= E_{S+W}\left\{\int_0^{s+w} (1/\Phi) \exp(-x/\Phi) dx\right\} \\ &= E_{S+W}\{1 - \exp(-(s+w)/\Phi)\}. \end{aligned} \tag{15}$$

As S and W are independent variables, we further obtain

$$P_{out}^t = 1 - E_S\{\exp(-S/\Phi)\} \times E_W\{\exp(-W/\Phi)\}. \tag{16}$$

Since variable S is a constant, E_S can be expressed by

$$E_S\{\exp(-S/\Phi)\} = \exp(-\left(N_0\gamma_{th}\right)/\Phi). \quad (17)$$

We can also derive the PDF of W from the PDF of $P_{U,B}^{t+1}$, which is given by

$$\begin{aligned} f_W(w) &= \frac{d}{dw}P(W \le w) = \frac{d}{dw}P(\frac{N_0\gamma_{th}}{ay} \le w) \\ &= \frac{N_0\gamma_{th}}{aw^2} \times \frac{1}{\Psi}\exp(-\frac{N_0\gamma_{th}}{a\Psi w}), \end{aligned} \quad (18)$$

where $\Psi = P_U^{t+1}(d_B^{t+1})^{-\alpha}$. Thus, E_W can be expressed as

$$\begin{aligned} E_W\{\exp(-\frac{W}{\Phi})\} &= \frac{1}{\Psi} \times \int_0^{+\infty} \exp(-\frac{w}{\Phi}) \\ &\quad \times \exp(-\frac{N_0\gamma_{th}}{aYw}) \times \frac{N_0\gamma_{th}}{aw^2}dw. \end{aligned} \quad (19)$$

By substituting (17) and (19) into (16), we have

$$\begin{aligned} P_{out}^t &= 1 - \frac{1}{\Psi}\exp(-\frac{N_0\gamma_{th}}{\Phi}) \times \int_0^{+\infty} \exp(-\frac{w}{\Phi}) \\ &\quad \times \exp(-\frac{N_0\gamma_{th}}{a\Psi w}) \times \frac{N_0\gamma_{th}}{aw^2}dw. \end{aligned} \quad (20)$$

According to the results in [8], (20) can be rewritten as

$$\begin{aligned} P_{out}^t &= 1 - \exp(-\frac{N_0\gamma_{th}}{\Phi}) \times 2VK_{-1}(2V), \\ V &= \sqrt{(N_0\gamma_{th}(\Phi + N_0))\,/\,(\Phi\Psi)}, \end{aligned} \quad (21)$$

where $K_{-1}(x)$ is the negative first order modified Bessel function of the second kind. Since $\Phi \gg N_0$, V in (21) can be simplified as $V = \sqrt{\frac{N_0\gamma_{th}}{\Phi}}$. Note that the modified Bessel function of the second kind has the property $K_{-1}(x) = K_1(x)$. Thus, we expand $K_1(x)$ according to [8] and have

$$K_1(x) \simeq 1/x + x/2 \times \ln(x/2). \quad (22)$$

By substituting (22) into (21), the analytical approximate solution of the outage probability is shown as (8). □

Appendix B
Proof of Theorem 2

Proof: When $-\nabla P_{out}^t = 0$, the outage probability is minimized. In (11), it can be easily found that the root of $-\nabla P_{out}^t = 0$ contains $y_t = 0$ and $z_t = 0$, which means BS, MD, and UAV are collinear. The solution of x_t satisfies $\frac{L}{x_t} = 1 - \frac{N}{M}$, which can not be solved easily. When we substitute $x_t = L/2$, we have $\frac{L}{x_t} < 1 - \frac{N}{M}$. It can be proved that the right side of the inequation is monotonically increasing with x_t at $x_t = L/2$ while the left side is monotonically decreasing. Therefore, the solution of x_t exists in $0 < x_t < L/2$, showing that the UAV is closer to BS than to the MD. □

Appendix C
Proof of Theorem 3

Proof: As shown in (20) from Appendix A, both $P_{M,U}^t$ and $P_{U,B}^{t+1}$ are negatively related with P_{out}^t. Since received power is positively related with transmit power, the increment of transmit power decreases the outage probability. Therefore, minimum outage probability requires maximized total transmit power, i.e., $P_U^{t+1} + P_M^t = P_{max}$. □

Appendix D
Proof of Theorem 4

Proof: We substitute (8) into $\frac{d(P_{out})}{dP_U^{t+1}} = 0$ and assume that $P_{M,U}^t \gg N_0$. We then have

$$\ln\left(\frac{P_U^{t+1}}{N_0\gamma_{th}(d_B^{t+1})^\alpha}\right) = \frac{(P_U^{t+1})^2(d_M^t)^\alpha}{(P_{max} - P_U^{t+1})^2(d_B^{t+1})^\alpha} + 1. \quad (23)$$

With $\theta = \frac{P_U^{t+1}}{P_{max}}$ and $u = \frac{\theta}{1-\theta}$, equation (23) can be simplified as

$$u^2 = \ln(B/A) + \ln\theta, \quad (24)$$

where $A = \exp\frac{(d_M^t)^\alpha}{(d_B^{t+1})^\alpha}$, and $B = \frac{P_{max}}{eN_0\gamma_{th}(d_B^{t+1})^\alpha}$. Using Taylor expansion, $\ln(\theta) = \theta - 1 + o(\theta) \simeq -\frac{1}{u+1}$, and u is the root of the following equation,

$$u^3 + u^2 - u\ln(B/A) + 1 - \ln(B/A) = 0. \quad (25)$$

It is solved that $u = \left(-q/2 + \sqrt{q^2/4 + p^3/27}\right)^{1/3} + \left(-q/2 + \sqrt{q^2/4 - p^3/27}\right)^{1/3}$, where $p = -\ln\ (B/A) - 1/3$, and $q = 2 + 9\ln\ (B/A) + 27(1 - \ln\ (B/A))^2/27$. The approximate solution for the transmit power is $P_M^t = \frac{P_{max}}{u}$, and $P_U^{t+1} = P_{max} - P_M^t$. The power control solution is determined by the ratio of A and B, which is mostly affected by d_M^t and d_B^{t+1}. The key factor of power control is d_M^t/d_B^{t+1}, since A is an exponential function of d_M^t and d_B^{t+1}.

When $d_M^t \ll d_B^{t+1}$, we have $A \simeq 1$, and $B \gg A$, therefore, $|\ln\frac{B}{A}| \gg 1$. When $d_M^t \gg d_B^{t+1}$, it is shown that $A \gg B$ because A is an exponential function of d_M^t, and we also have $|\ln\frac{B}{A}| \gg 1$. In both cases, (25) can be simplified as $u = 1$. The power control is given as $P_M^t = P_{max}$, and $P_U^{t+1} = 0$. It means that the relay will be redundant if it is too close to the source or destination. □

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