TRAJECTORY AND POWER OPTIMIZATION FOR UAV-ASSISTED COMMUNICATION USING RANDOM SEARCH ALGORITHM

TỐI ƯU QUỸ ĐẠO VÀ CÔNG SUẤT TRONG HỆ THỐNG THÔNG TIN CÓ UAV HỖ TRỢ BẰNG THUẬT TOÁN TÌM KIẾM NGẪU NHIÊN

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Abstract:

In this paper, we propose a joint trajectory and transmit power optimization framework for a UAV-assisted communication system employing a Decode-and-Forward (DF) relay protocol. The objective is to maximize the cumulative achievable rate while satisfying instantaneous transmit power and mobility constraints. The UAV moves from a predefined initial position to a fixed destination and acts as an aerial relay between a ground source and destination. A Random Search (RS)-based algorithm is developed to jointly optimize the UAV trajectory and per-step power allocation over discrete time intervals. The proposed approach is compared with a conventional straight-line baseline with fixed maximum transmit power. Simulation results show that the RS-based method improves cumulative spectral efficiency by 14.58% while satisfying all constraints and reducing average transmit power. These results confirm that the proposed framework provides an effective and computationally efficient solution for UAV-assisted wireless communications in environments with position-dependent channel impairments.

Keywords:

UAV-assisted communication; Decode-and-Forward relay; Random Search; Trajectory optimization; Power allocation; Position-dependent blockage.

Tóm tắt:

Trong bài báo này, chúng tôi đề xuất một khung tối ưu đồng thời quỹ đạo bay và công suất phát cho hệ thống thông tin có UAV hỗ trợ sử dụng giao thức chuyển tiếp giải mã–chuyển tiếp (Decode-and-Forward, DF). Mục tiêu là cực đại hóa tốc độ truyền tích lũy trong khi vẫn đảm bảo các ràng buộc công suất phát tức thời và ràng buộc cơ động của UAV. UAV di chuyển từ vị trí khởi đầu xác định đến điểm đích cố định và đóng vai trò là trạm chuyển tiếp trên không giữa nguồn và đích mặt đất. Một thuật toán dựa trên Tìm kiếm Ngẫu nhiên (Random Search – RS) được xây dựng để đồng thời tối ưu quỹ đạo UAV và phân bổ công suất theo từng bước thời gian rời rạc. Phương pháp đề xuất được so sánh với phương pháp chuẩn trong đó UAV bay theo đường thẳng và sử dụng công suất cực đại cố định. Kết quả mô phỏng cho thấy phương pháp RS giúp cải thiện hiệu suất phổ tích lũy 14,58% so với phương pháp chuẩn, đồng thời thỏa mãn đầy đủ các ràng buộc vật lý và giảm công suất phát trung bình. Kết quả này khẳng định tính hiệu quả và độ phức tạp tính toán thấp của phương pháp đề xuất đối với hệ thống thông tin không dây có UAV hỗ trợ trong môi trường có suy hao phụ thuộc vị trí.

Từ khóa: Truyền thông có UAV hỗ trợ; Chuyển tiếp giải mã–chuyển tiếp (DF); Thuật toán Tìm kiếm Ngẫu nhiên; Tối ưu quỹ đạo; Phân bổ công suất; Suy hao phụ thuộc vị trí.

1. INTRODUCTION

Recent advances in Unmanned Aerial Vehicles (UAVs) have significantly expanded their applications in wireless communications, where UAVs can operate as aerial base stations or mobile relays to enhance coverage, flexibility, and throughput. However, achieving high communication capacity while maintaining energy efficiency and feasible flight trajectories remains a challenging problem, particularly under practical mobility and power constraints.

Several studies have investigated joint trajectory and resource optimization for UAV-assisted communication systems. Zeng and Zhang [1] demonstrated that joint trajectory and transmit power optimization can substantially improve energy efficiency. Zheng et al. [2] addressed trajectory and velocity planning for UAV-enabled IoT data collection, achieving reduced flight time and energy consumption. Huang et al. [3] studied UAV base stations under in-band backhaul constraints, jointly optimizing trajectory and resource allocation to enhance throughput and fairness. Lu et al. [4] further considered UAV-powered communication systems with joint trajectory and energy management. The problem of UAV placement and trajectory optimization has been extensively studied in the literature, as reviewed in [5]. In maritime communication scenarios, Deng et al. [6] proposed a dual-UAV relay framework for energy-efficient data collection, while Wang et al. [7] and Jia et al. [8] investigated secure UAV-assisted communications under adversarial channel conditions, focusing on secrecy rate and energy efficiency optimization.

Although these approaches achieve promising performance, many rely on computationally intensive optimization techniques such as successive convex approximation or iterative search algorithms, which may limit real-time implementation.

Motivated by these challenges, this paper proposes a Random Search (RS)-based framework for joint trajectory and transmit power optimization in a discrete-time UAV-assisted communication system. The RS algorithm does not require gradient information or convex reformulation, resulting in a simple and computationally efficient solution. The proposed approach is evaluated against a conventional straight-line baseline with fixed maximum transmit power. Simulation results demonstrate that the RS-based method achieves higher cumulative spectral efficiency under practical mobility and power constraints.

The remainder of this paper is organized as follows. Section 2 presents the system model and problem formulation. Section 3 provides simulation results and discussion. Section 4 concludes the paper.

2. METHODOLOGY

This section presents the system model, the problem formulation for joint UAV trajectory and power optimization, and the proposed Random Search (RS)-based optimization framework. A conventional straight-line baseline is also introduced for performance comparison.

2.1. System model

We consider a point-to-point wireless communication system assisted by an Unmanned Aerial Vehicle (UAV) acting as a Decode-and-Forward (DF) relay between a ground source and a ground destination. The source is located at *(0,0),* and the destination is located at *(D,0)*, where $D = 2000\ m$. The UAV flies at a fixed altitude $H = 100\ m$. The total flight duration T is divided into $N=20$ equal time steps, each with duration $\Delta t = \frac{T}{N}$. The horizontal position of the UAV at time step $i \in \{1,2,\ldots,N\}$ is denoted by (x_i, y_i). The UAV is required to start from $(x_1, y_1) = (0,0)$ and arrive at $(x_N, y_N) = (D,0)$. The transmit powers at time step i are denoted by $P_{a,i}$ (source-to-UAV link) and $P_{u,i}$ (UAV-to-destination link), measured in watts (W). The receiver noise is modeled as additive white Gaussian noise (AWGN) with power σ^2, and γ_0 represents a reference channel gain incorporating antenna gains and reference path-loss.

The large-scale channel power gains of the two hops are modeled according to the free-space path-loss model as

$$\bar{g}_{a,i} = \frac{\gamma_0}{H^2 + x_i^2 + y_i^2}, \quad (1)$$

$$\bar{g}_{u,i} = \frac{\gamma_0}{H^2 + (D - x_i)^2 + y_i^2} \quad (2)$$

To emulate realistic urban propagation conditions, a position-dependent blockage effect is incorporated. Specifically, when the UAV lies within the horizontal corridor $x \in [X1, X2]$ and close to the direct path $y \approx 0$, an additional attenuation of L_{block} dB is applied. The blockage factor $b(x,y) \in (0,1]$ is defined as

$$b(x,y) = 1 - exp\left(-\left(\frac{y}{Y_w}\right)^2\right)\left(1 - 10^{\frac{-L_{block}}{10}}\right),\ x \in [X_1, X_2] \quad (3a)$$

$$b(x,y) = 1, \text{ otherwise} \quad (3b)$$

where $X_1 = 300\ m, X_2 = 1700\ m, and\ L_{block} = 28\ dB$. The effective channel gains become

$$g_{a,i} = \bar{g}_{a,i} b(x_i, y_i), g_{u,i} = \bar{g}_{u,i} b(x_i, y_i) \quad (4)$$

Under the DF relaying protocol, the instantaneous achievable rate at time step i is determined by the weaker hop and is given by

$$R_i = \frac{1}{2} min\left\{log_2\left(1 + \frac{P_{a,i} g_{a,i}}{\sigma^2}\right), log_2\left(1 + \frac{P_{u,i} g_{u,i}}{\sigma^2}\right)\right\} \quad (5)$$

The factor *1/2* accounts for the two-phase transmission of the DF relay. The cumulative achievable rate over the whole trajectory is $R_{total} = \sum_{i=1}^{N} R_i$.

2.2. Problem Formulation

Based on the system model presented in Section 2.1, the objective is to jointly optimize the UAV trajectory and transmit power allocation in order to maximize the cumulative achievable rate over the entire flight duration. The optimization variables include the UAV horizontal coordinates (x_i, y_i) and the transmit powers $P_{a,i}$ and $P_{u,i}$, for $i = 1,2,\ldots,N$. The optimization problem can be formulated as

$$max \sum_{i=1}^{N} R_i \quad (6)$$

Where the optimization variables are $\{x_i, y_i, P_{a,i}, P_{u,i}\}$ for $i = 1,2,\ldots,N$ and the optimization is performed over all time steps. R_i is defined in (5). The transmit powers at each time step are subject to instantaneous power constraints given by

$$0 \le P_{a,i} \le P_a^{max}, 0 \le P_{u,i} \le P_u^{max}, \forall i \quad (7)$$

and the UAV mobility is limited by the maximum horizontal speed V^{max}, leading to the displacement constraint

$$\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \leq V^{max}\Delta t \text{ , } \forall i = 2, \dots, N \quad (8)$$

In addition, the UAV starts from the initial location (x_0, y_0) and must reach the destination point $(D, 0)$, where D denotes the horizontal distance between the source and the destination.

$$(x_1, y_1) = (x_0, y_0), (x_N, y_N) = (x_{dest}, y_{dest}) \quad (9)$$

where $(x_{dest}, y_{dest}) = (D, 0)$

Since the above problem is non-convex due to the coupled trajectory and power variables as well as the nonlinear rate expression, it is difficult to solve directly using conventional optimization techniques. Therefore, the constrained problem is transformed into a penalized minimization form suitable for the Random Search algorithm. The penalized objective function is defined as

$$L = -\sum_{i=1}^{N} R_i + \lambda_1 A + \lambda_2 B + \lambda_3 C \quad (10)$$

where

$$A = \sum_{i=1}^{N} \max\left(P_{a,i} - P_a^{max}, 0\right)$$

$$B = \sum_{i=1}^{N} \max\left(P_{u,i} - P_u^{max}, 0\right)$$

$$C = \sum_{i=2}^{N} \max(\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} - V^{max}\Delta t, 0)$$

where λ_1, λ_2 and λ_3 are positive penalty coefficients. Minimizing L is equivalent to maximizing the cumulative achievable rate while penalizing violations of the instantaneous power and mobility constraints. When the penalty coefficients are sufficiently large, infeasible solutions result in large objective values, and at convergence, the penalty terms approach zero, ensuring that all constraints are satisfied.

2.3. Random Search–Based Optimization

The formulated optimization problem is non-convex due to the coupling between UAV trajectory variables and transmit power allocation, as well as the nonlinear logarithmic rate expression. To solve this problem with low computational complexity, a Random Search (RS)–based optimization framework is adopted.

Random Search operates by iteratively generating candidate solutions within predefined feasible bounds and evaluating them using the penalized objective function defined in (10). At each iteration, a population of candidate trajectories and power allocation vectors is randomly sampled. The transmit powers $\boldsymbol{P_{a,i}}$ and $\boldsymbol{P_{u,i}}$ are uniformly generated within the interval $[0, \boldsymbol{P_a^{max}}]$ and $[0, \boldsymbol{P_u^{max}}]$, respectively. The UAV trajectory is generated such that the displacement between two consecutive time steps does not exceed the maximum allowable horizontal distance $\boldsymbol{V^{max}\Delta t}$, thereby satisfying the mobility constraint by construction.

For each candidate solution, the cumulative achievable rate is computed according to (5), and the penalized objective function in (10) is evaluated. If the new candidate produces a lower objective value, it replaces the current best solution. This process is repeated for a fixed number of iterations and population size until convergence.

Let N_{iter} denote the number of RS iterations and P_{size} the population size per iteration. Since each candidate evaluation requires computing the achievable rate across N time steps, the overall computational complexity of the RS algorithm scales linearly as $\mathcal{O}(N_{iter}P_{size}N)$, where N_{iter} is the number of iterations, P_{size} is the population size, and N is the number of trajectory points.

This linear complexity makes the proposed approach computationally efficient and suitable for UAV-assisted communication systems where real-time or low-complexity implementation is required.

Compared with gradient-based or successive convex approximation methods, the RS algorithm does not require derivative information, convex reformulation, or auxiliary variables. Although it is simple in structure, simulation results demonstrate that it can effectively improve cumulative system capacity while satisfying instantaneous power and mobility constraints.

2.4. Conventional baseline approach

For comparison, a straight-line trajectory is adopted as the baseline. The UAV moves uniformly from the initial to the final position along a direct horizontal path, and both transmit powers are fixed at their maximum values, i.e., $P_{a,i} = P_a^{max}$ and $P_{u,i} = P_u^{max}$ for all time steps. This baseline does not exploit trajectory adaptation or dynamic power allocation and serves as a reference for performance evaluation.

3. RESULTS AND DISCUSSION

This section evaluates the RS-based joint trajectory and power optimization under position-dependent blockage. The source–destination distance is 2000 m, and the UAV altitude is fixed at 100 m. A blockage corridor with 28 dB attenuation over $x \in [300, 700]\ m$ creates non-uniform channels. Simulation parameters are listed in Table I, and the reference gain γ_0 corresponds to the path loss at $d_0 = 1m$.

Table 1. Simulation Parameters

Parameter	Value
Distance between source and destination D	2000 m
UAV altitude H	100 m
Total flight time T	200 s
Number of time steps N	20
Maximum UAV speed Vmax	20 m/s
Maximum transmit power Pa_max, Pu_max	10 W
Noise power σ^2	10^{-12} W
Reference channel gain γ_0	10^6
Penalty coefficients λ_1, λ_2, λ_3	100, 100, 2000
Blockage attenuation Lblock	28 dB

Based on the above configuration, the performance of the proposed RS-based method is compared with the traditional straight-line baseline in terms of convergence behavior, power allocation, trajectory adaptation, and cumulative achievable rate.

Figure 1 presents the convergence behavior of the RS algorithm. The fitness value, defined as the negative cumulative achievable rate, decreases rapidly during the first 100 iterations and stabilizes after approximately 300 iterations.

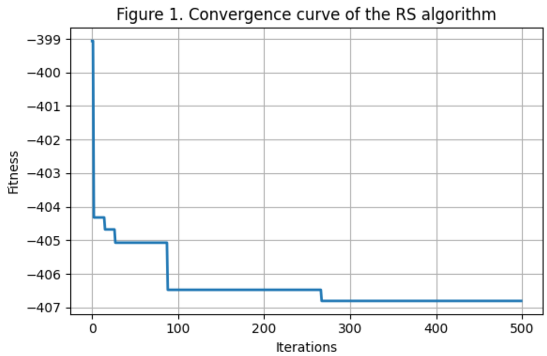

Fig. 1. Convergence of the RS algorithm

The final fitness converges to −406.80, corresponding to a cumulative achievable rate of 406.80 bps/Hz. Importantly, the final penalty values for both power and mobility constraints are zero, indicating that the obtained solution strictly satisfies all instantaneous transmit power and displacement constraints. The convergence behavior indicates that the RS algorithm effectively explores the feasible solution space despite the non-convex coupling between trajectory and power variables.

Figure 2 illustrates the optimized transmit power allocation per time step for both the source-to-UAV link and the UAV-to-destination link. Unlike the traditional baseline method, which employs constant maximum transmit power, the RS-based solution dynamically adjusts power levels according to UAV position and channel quality.

The average transmit powers are 5.48 W for the source and 5.13 W for the UAV, both remaining below the maximum allowable value of 10 W, which confirms that the performance improvement is achieved through joint trajectory and power adaptation rather than excessive power usage.

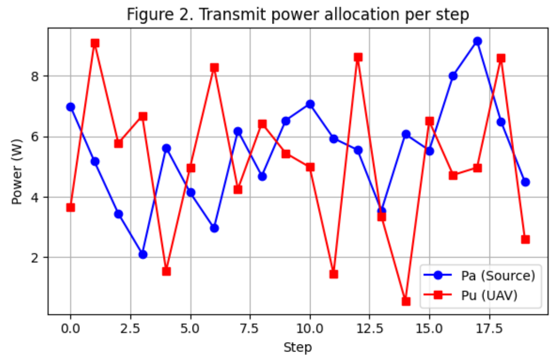

Fig. 2. Optimized transmit power per time step

This demonstrates that the observed performance improvement is not achieved by increasing power consumption but by intelligently coordinating trajectory adaptation and power distribution in response to position-dependent channel variations.

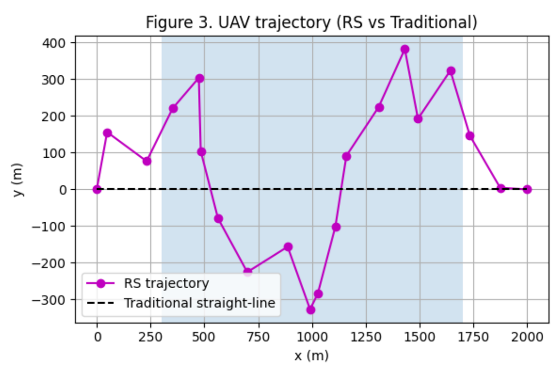

Fig. 3. UAV trajectory comparison: RS versus straight-line baseline

Figure 3 compares the UAV trajectories obtained by the RS-based method and the traditional straight-line approach. The straight-line trajectory passes directly through the blockage corridor, where the channel suffers from severe attenuation. In contrast, the RS-based trajectory deviates from the horizontal axis and partially avoids the high-loss region. The presence of the blockage corridor breaks the spatial symmetry of the propagation environment, which explains why a curved trajectory yields higher cumulative capacity than the straight-line path. The trajectory deviation is therefore physically justified and not a random artifact of the search process.

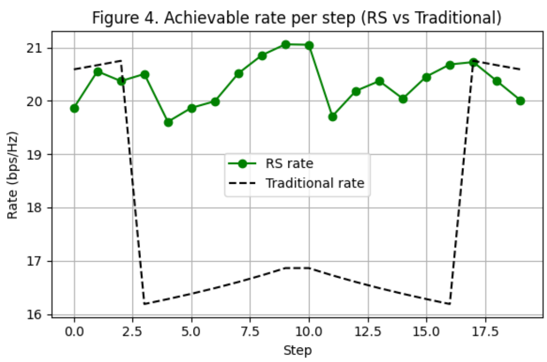

Fig. 4. Achievable rate per time step: RS versus straight-line baseline

Figure 4 further illustrates the achievable rate per time step under both methods. The RS-based approach consistently outperforms the traditional baseline, particularly within the blockage corridor, where the straight-line trajectory experiences significant rate degradation. Outside the blocked region, the performance gap becomes smaller, indicating that trajectory adaptation provides the greatest benefit in adverse propagation conditions. Overall, the RS-based solution achieves a cumulative capacity of 406.80 bps/Hz, compared to 355.05 bps/Hz for the traditional method, corresponding to a 14.58% improvement in spectral efficiency.

Table 2 summarizes the quantitative performance comparison between the proposed RS-based method and the traditional straight-line baseline, clearly highlighting the capacity gain and improved power efficiency achieved through joint trajectory and power optimization.

Table 2. Performance comparison between the proposed RS-based method and the traditional straight-line baseline

Metric	Traditional method	RS-Based method
Total capacity (bps/Hz)	355.05	406.80
Capacity improvement (%)	–	14.58%
Average source power (W)	10.00	5.48
Average UAV power (W)	10.00	5.13
Maximum UAV speed (m/s)	20	20

4. CONCLUSION

This paper proposes a Random Search (RS)–based method for joint trajectory and transmit power optimization in a UAV-assisted Decode-and-Forward communication system under position-dependent blockage conditions. The non-convex optimization problem was reformulated into a penalized objective framework to enforce instantaneous power and mobility constraints. Simulation results demonstrate that the proposed method achieves a 14.58% improvement in cumulative spectral efficiency compared with the conventional straight-line baseline, while strictly satisfying all constraints and operating below the maximum transmit power limits. These findings indicate that the RS-based approach provides an effective and computationally efficient solution for UAV-assisted relay communications in spatially heterogeneous wireless environments.

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