TẠP CHÍ KHOA HỌC VÀ CÔNG NGHỆ NĂNG LƯỢNG - TRƯỜNG ĐẠI HỌC ĐIỆN LỰC
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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 an optimization approach for the trajectory and transmission power allocation of a UAV-assisted communication system using the Random Search (RS) algorithm. The objective is to maximize the overall communication capacity while ensuring constraints on power consumption and movement feasibility. The UAV moves from a predefined starting location to a destination point while serving as a relay between a source and destination. The RS algorithm is employed to jointly optimize the UAV's trajectory and power allocation over multiple discrete steps. We evaluate the performance of the proposed RS-based solution and compare it with a traditional method in which the UAV follows a fixed straight-line trajectory with uniform power allocation. Simulation results show that the RS method yields a significantly higher cumulative capacity while offering flexibility in trajectory planning and power efficiency. The convergence behavior, power profiles, and UAV trajectories are also illustrated, highlighting the effectiveness of the RS approach for UAV-based wireless communications.

Keywords: UAV-assisted communication; Random Search algorithm; Trajectory optimization; Power allocation; Wireless communication.

Tóm tắt:

Trong bài viết này, chúng tôi đề xuất một phương pháp tối ưu hóa quỹ đạo và phân bổ công suất truyền của hệ thống thông tin sử dụng UAV hỗ trợ, dựa trên thuật toán Tìm kiếm Ngẫu nhiên (Random Search - RS). Mục tiêu là tối đa hóa tổng dung lượng truyền thông trong khi vẫn đảm bảo các ràng buộc về tiêu thụ công suất và khả năng di chuyển. UAV di chuyển từ một vị trí xuất phát xác định đến điểm đích, đóng vai trò là một nút chuyển tiếp giữa nguồn và đích. Thuật toán RS được sử dụng để đồng thời tối ưu hóa quỹ đạo và phân bổ công suất UAV theo các bước rời rạc. Chúng tôi đánh giá hiệu suất của giải pháp sử dụng RS và so sánh với phương pháp truyền thống, trong đó UAV di chuyển theo đường thẳng cố định và phân bổ công suất đồng đều. Kết quả mô phỏng cho thấy phương pháp RS mang lại dung lượng truyền tích lũy cao hơn đáng kể, đồng thời cung cấp sự linh hoạt trong lập kế hoạch quỹ đạo và hiệu quả sử dụng công suất. Biểu đồ hội tụ, hồ sơ công suất và quỹ đạo UAV cũng được minh họa, cho thấy hiệu quả của phương pháp RS trong các hệ thống truyền thông không dây sử dụng UAV.

Từ khóa: Truyền thông UAV hỗ trợ; Thuật toán Tìm kiếm ngẫu nhiên; Tối ưu quỹ đạo; Phân bổ công suất; Truyền thông không dây.

1. INTRODUCTION

Recent advances in Unmanned Aerial Vehicles (UAVs) have opened new frontiers in wireless communication, leveraging UAVs as aerial base stations or mobile relays to enhance coverage, flexibility, and throughput. However, maximizing communication capacity while ensuring power efficiency and trajectory feasibility remains challenging in dynamic environments.

Zeng and Zhang [1] were among the first to jointly optimize UAV trajectory and transmit power, demonstrating substantial energy efficiency gains over heuristic paths. Prior to this, Zheng et al. [2] addressed UAV trajectory and speed planning for IoT data collection using projection-based discretization, achieving significant reductions in power and flight time. More recently, Huang et al. [3] extended trajectory and resource allocation designs to UAV base stations with in-band backhaul constraints, improving user fairness and throughput.

Lu et al. [4] examined UAV-powered communication systems, jointly optimizing energy replenishment, trajectory, and power allocation in IoT scenarios. A comprehensive survey by Mazaherifar and Mostafavi [5] has cataloged these trajectory designs and highlighted the critical interplay between UAV mobility and communication resource management.

In specialized maritime environments, Deng et al. [6] proposed a dual-UAV relay framework optimized for minimal energy consumption during data collection, while Wang et al. [7] and Jia et al. [8] focused on secure and energy-efficient UAV-aided communication in adversarial or eavesdropper-rich maritime channels, involving secrecy rate and SINR optimizations under complex constraints.

Although these methods deliver robust performance, they predominantly rely on computationally heavy techniques, such as successive convex approximation or iterative search, which can be suboptimal for real-time deployment.

In light of this, we propose a Random Search (RS)-based optimization for joint trajectory and power allocation in finite-step UAV networks. This method offers simplicity, adaptability, and low computational load. We evaluate RS against a conventional straight-line, fixed-power baseline. Simulation results reveal RS achieves superior cumulative capacity under stringent power and mobility constraints, suggesting a practical alternative for low-complexity UAV-enabled communications.

The paper is organized as follows: Section 2 reviews related work; Section 3 outlines the methodology; Section 4 presents results and discussion; Section 5 concludes the study and suggests future work.

2. RELATED WORKS

Recent advances in UAV-assisted communication have led to a variety of optimization frameworks targeting energy efficiency, capacity maximization, and secure transmission. To contextualize our proposed approach, we review relevant literature on trajectory and resource optimization in UAV communication systems. Zeng and Zhang [1] were among the first to explore joint trajectory and power optimization for UAV-enabled wireless links, laying a foundation for energy-efficient designs. Expanding on this direction, Zheng et al. [2] formulated a joint trajectory and speed optimization problem for IoT data collection and solved it using a projection-based algorithm to reduce mission time and energy consumption. Trajectory optimization in the presence of backhaul constraints was addressed by Huang et al. [3], who developed a joint trajectory and resource allocation framework for UAV base stations under in-band communication limitations. Their work emphasized balancing user fairness and throughput. Further expanding UAV roles, Lu et al. [4] considered UAV-powered communication networks, where both trajectory and resource allocation were optimized alongside energy replenishment strategies. This integrated view is essential in IoT-centric deployments.

Mazaherifar and Mostafavi [5] offered a comprehensive survey summarizing various UAV placement and trajectory optimization strategies, classifying them based on problem structure and solutions techniques. Their findings highlight how mobility and communication design must be co-optimized to achieve system-wide efficiency. In maritime contexts, Deng et al. [6] proposed a dual-UAV relay system for energy-efficient data collection, tackling the challenge of link reliability over dynamic marine channels. Meanwhile, Wang et al. [7] and Jia et al. [8] examined secure UAV-aided communications, proposing secrecy energy-efficient designs to counter eavesdropping threats while managing transmit power and UAV trajectories under uncertain channel conditions. While the aforementioned studies deliver strong performance using advanced optimization techniques (e.g., successive convex approximation, iterative search, or learning-based models), they often incur significant computational costs, making real-time adaptation challenging. By contrast, our study proposes a Random Search (RS)-based strategy for joint trajectory and power optimization in UAV networks. The RS method does not rely on gradient information or complex transformations, making it suitable for practical deployment in time-sensitive or resource-constrained scenarios. Moreover, we establish a baseline using a traditional fixed-power, straight-path method to highlight the performance gains of our RS approach. This comparative analysis, supported by empirical simulations, demonstrates that RS can achieve competitive cumulative capacity with significantly reduced computational burden.

3. 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. The baseline traditional method is also described for comparative analysis.

3.1. System model

We consider a point-to-point communication system assisted by an Unmanned Aerial Vehicle (UAV), where the UAV serves as a relay between a static source and destination. The source and destination are placed on the ground at a distance D=2000 meters apart, while the UAV flies at a fixed altitude H=100 meters. The UAV trajectory is discretized into N=20 steps, and at each step, it can adjust its horizontal velocity and transmission power.

Let $x = [x_1, x_2, \dots, x_N]$ and y= $[y_1, y_2, \dots, y_N]$

denote the horizontal position of the UAV at each time step. Let $\mathbf{P}_a$ and $\mathbf{P}_u$ denote the power values from the source to the UAV and from the UAV to the destination, respectively. The received signal strength is modeled using a path loss model with geometric parameters and a constant γ_o. The signal-to-noise ratio (SNR) at each step is computed according to Equation (1)

$$\gamma = \frac{P_a P_u \gamma_a \gamma_u}{P_a \gamma_a \sigma^2 + P_u \gamma_u \sigma^2 + \sigma^4} \quad (1)$$

Where γ_a and γ_u are path loss components from source to UAV and UAV to destination, and σ^2 is the noise power.

The achievable rate (in bps/Hz) at each step is calculated as shown in (2).

$$R = \frac{1}{2}\log_2(1+\gamma) \quad (2)$$

3.2. Problem formulation

Let the UAV trajectory be discretized into N time steps. At each time step $i\epsilon\{1,2,\dots,N\}$, we optimize the following decision variables:

x_i,y_i are horizontal coordinates of the UAV.

$P_{a,i}$ and $P_{u,i}$ are transmit power from source to UAV at step *i* and transmit power from UAV to destination at step *i*.

v_i is UAV velocity at step i.

The path loss between source–UAV and UAV–destination is modeled respectively at each step i as shown in (3) and (4).

$$\gamma_{a,i} = \frac{\gamma_0}{H^2 + x_i^2 + y_i^2} \quad (3)$$

$$\gamma_{u,i} = \frac{\gamma_0}{H^2 + (D - x_i)^2 + y_i^2} \quad (4)$$

The instantaneous signal-to-noise ratio (SNR) at step i is calculated as shown in (5).

$$\gamma_i = \frac{P_{a,i} P_{u,i} \gamma_{a,i} \gamma_{u,i}}{P_{a,i}\gamma_{a,i}\sigma^2 + P_{u,i}\gamma_{u,i}\sigma^2 + \sigma^4} \quad (5)$$

The achievable rate is calculated as shown in (6).

$$R_i = \frac{1}{2}\log_2(1+\gamma_i) \quad (6)$$

We aim to maximize the sum-rate over the entire trajectory, which is computed according to Equation (7).

$$\max_{p_a, p_{u,x,y,v}} \sum_{i=1}^{N} R_i \quad (7)$$

Subject to:

- Transmit power limits:
  $0 \le P_{a,i} \le P_a^{max}$, $0 \le P_{u,i} \le P_u^{max}, \forall i$
- Mobility constraints:
  $\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \le \frac{v_i T}{N}, \forall i = 2, \dots, N$

Initial and final position constraints:

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

(x_0,y_0) is initial position of the UAV

(x_{dest}, y_{dest}) is final position (destination) of the UAV.

To incorporate these constraints into a soft-constrained optimization framework, we define the penalized objective function as shown in Equation (8).

$$L = -\sum_{i=1}^{N} R_i + \lambda_1 . max\left(\sum_{i=1}^{N} P_{a,i} - N.P_a^{max}, 0\right) + \lambda_2 . max\left(\sum_{i=1}^{N} P_{u,i} - N.P_u^{max}, 0\right) + \lambda_3 . \sum_{i=2}^{N} \delta_i \quad (8)$$

where:

$$\delta_i = max\left(\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} - \frac{v_i T}{N}, 0\right)$$

and λ_1, λ_2, λ_3 are penalty coefficients for power and trajectory violations, T is total flight time, N is the number of time steps, γ_0, σ^2, *H, and D* are system constants. *H* is fixed altitude of the UAV (in meters) *D* is istance between source and destination (in meters). is noise power at the receiver. Thus, the problem becomes a minimization of *L*, which balances maximizing capacity while penalizing constraint violations in power and movement. v_i is UAV horizontal speed at time step i (in m/s).

3.3. Random search-based optimization

Due to the non-convexity and high dimensionality of the problem, we adopt Random Search (RS) as a lightweight metaheuristic approach. RS iteratively samples random candidate solutions from a uniform distribution within the feasible bounds of the decision variables. The best candidate in terms of fitness (i.e., minimized cost function) is retained at each iteration.

The key steps in RS include:

- Randomly generating position, velocity, and power variables.
- Evaluating the objective function using the system model.
- Updating the best solution if the current candidate outperforms the previous.
- Repeating for a fixed number of iterations and population size.

This simple framework avoids the complexity of gradient computation or heuristic crossover operations, making it suitable for low-complexity deployments or edge devices.

3.4. Traditional baseline approach

For comparison, we implement a conventional straight-line trajectory where the UAV moves uniformly from the source to the destination. Both transmission powers $\mathbf{P_a}$ and $\mathbf{P_u}$ are fixed at their average allowable values across all steps.

This method serves as a benchmark to evaluate the performance gain of RS-based trajectory and power optimization. While simple and deterministic, the traditional approach does not account for channel variations or energy efficiency in movement.

4. RESULTS AND DISCUSSION

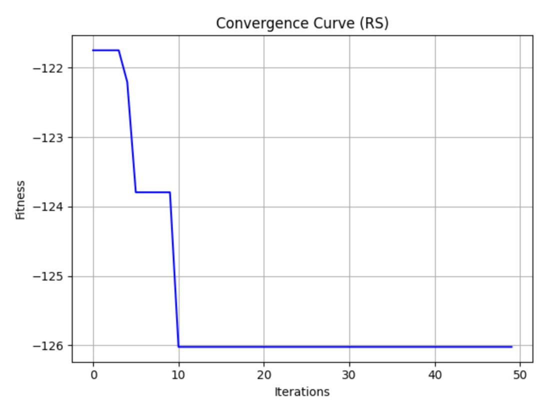

Figure 1. Convergence curve of the random search algorithm

In this section, we evaluate the performance of the proposed joint trajectory and power optimization scheme using the Random Search (RS) algorithm. Simulation results are obtained in a two-dimensional environment with a source located at the origin and a destination located 2000 meters away. The communication system includes a UAV relay that dynamically adjusts its trajectory and transmission power to maximize the overall transmission capacity. We compare our proposed RS-based approach with a traditional fixed-path, fixed-power benchmark to highlight the advantages of joint optimization.

Figure 1 shows the convergence of the RS algorithm over 50 iterations. The fitness value improves rapidly during the first 10 iterations and stabilizes afterward around –126, indicating that RS quickly finds a near-optimal solution and maintains it. This behavior highlights the algorithm's efficiency in low-complexity optimization settings.

Figure 2 illustrates the average transmit power of the source (Pa) and UAV (Pu) over the trajectory. Initially, Pu is higher due to relay adjustments but gradually decreases and aligns with Pa.

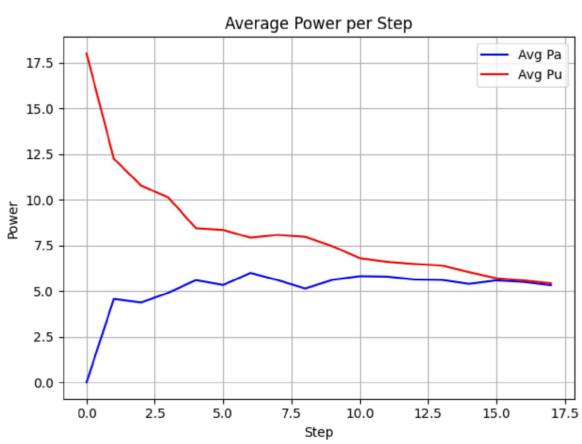

Figure 2. Average transmits power allocation per step

The balanced convergence of both power levels demonstrates that RS effectively manages energy consumption while maintaining communication quality.

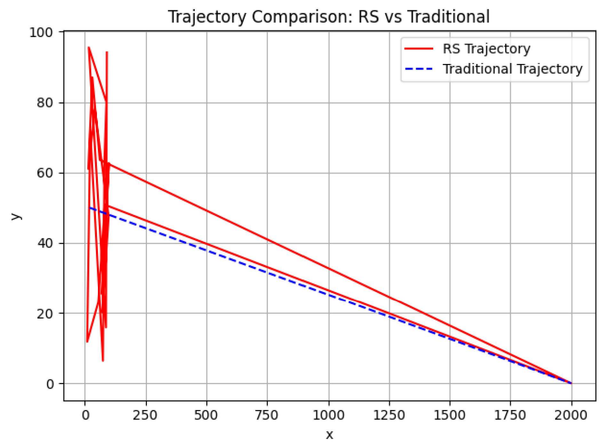

Figure 3. UAV trajectory comparison between RS-based method and traditional linear path

Figure 3 illustrates the flight trajectories of the UAV under two schemes: the proposed RS-based method and the traditional linear method. The RS-based trajectory shows a more adaptive flight path, where the UAV deviates from a straight line to position itself advantageously with respect to the communication channel conditions. This flexibility helps the UAV avoid high path-loss areas and maintain stronger links with both the source and destination. In contrast, the traditional method follows a fixed straight-line path, which does not consider real-time communication efficiency. The RS-based trajectory demonstrates the benefit of mobility-aware optimization, contributing to improved capacity and energy efficiency.

Table 1 summarizes the performance comparison between the RS-based method and the traditional approach.

Table 1. Performance comparison of rs-based and traditional methods

Metric	Traditional method	RS-Based method
Total capacity (bps/Hz)	63.47	80.52
Average source power Pa (mW)	10.00	9.83
Average UAV power Pu (mW)	10.00	9.74

The RS method achieves a 27% higher total capacity (80.52 and 63.47 bps/Hz) while consuming slightly less average power at both the source (Pa: 9.83 mW) and UAV (Pu: 9.74 mW). This demonstrates that RS offers better spectral and energy efficiency by dynamically adapting the UAV's trajectory and power allocation, unlike the fixed strategy in the baseline.

5. CONCLUSION

This study proposed a Random Search (RS)-based method for joint trajectory and power optimization in UAV-assisted wireless communication systems. By dynamically adjusting the UAV's flight path and transmission power, the RS-based approach achieved significantly higher communication capacity compared to the traditional fixed-path strategy, while maintaining lower average power consumption. Simulation results demonstrated that RS can improve spectral efficiency by approximately 27% without increasing energy usage.

Owing to its simplicity and low computational cost, the RS algorithm offers a promising lightweight alternative for real-time or resource-constrained UAV deployment scenarios. Future work may explore hybrid metaheuristic strategies or extend the model to multi-UAV cooperative networks and dynamic user distributions.

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Biography

Duong Thi Hang, was born in Bac Ninh, Vietnam. She received her Bachelor's degree in 2000, her Master's degree in 2006, and completed her Ph.D. in 2025, all from the University of Engineering and Technology, Vietnam National University, Hanoi. She is currently a lecturer at Electric Power University (EPU), Hanoi, Vietnam. Her main research interests include indoor localization using machine learning, optimization algorithms, and UAV-based communication systems.

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