

Joint Trajectory and Power Optimization for UAV-Relay: A Constraint Handling Approach with the Bat Algorithm

Pham Thi Quynh Trang¹, Duong Thi Hang², and Nguyen Viet Tuyen^{1,*}

¹ School of Electric and Electronic, Hanoi University of Industry, Hanoi, 100000, Vietnam

² Faculty of Electronics and Telecommunications, Electric Power University, Ha Noi, 100000, Vietnam
Email: pham.trang@hau.edu.vn (P.T.Q.T.); hangdt_dvt@epu.edu.vn (D.T.H.); nvtuyen@hau.edu.vn (N.V.T.)

*Corresponding author

Abstract— Unmanned Aerial Vehicles (UAVs) have emerged as flexible relay platforms capable of enhancing wireless connectivity in beyond-5G and 6G networks. This paper investigates the joint optimization of UAV trajectory and power allocation to maximize end-to-end throughput under practical mobility and power constraints. The problem is highly non-convex due to the strong coupling between trajectory variables and transmission power. To address this challenge, we develop a penalty-based metaheuristic framework that incorporates a constraint-handling mechanism into the Bat Algorithm (BAT). Simulation results show that the proposed BAT-based approach achieves significant throughput improvement, efficient power allocation, and fast convergence compared with baseline convex optimization and heuristic schemes. These findings highlight the potential of BAT for reliable and energy-efficient UAV-assisted communication in future wireless networks.

Keywords— UAV communications, bat algorithm, trajectory optimization, power allocation, metaheuristics

I. INTRODUCTION

The rapid evolution of beyond-5G (B5G) and 6G wireless networks has positioned Unmanned Aerial Vehicles (UAVs) as an increasingly important technology for extending coverage and enhancing connectivity. Owing to their high mobility, flexible deployment, and favorable Line-of-Sight (LoS) conditions with ground nodes, UAVs can operate as aerial base stations or mobile relays to support diverse applications, including emergency communication and disaster-response scenarios [1–3]. In UAV-assisted relay systems, the end-to-end throughput is strongly influenced by the joint behavior of the UAV's trajectory and its transmission power allocation. Unlike static relays, a mobile UAV can dynamically adjust its position to improve link quality and enhance network performance [4–6].

However, optimizing UAV trajectory and power allocation simultaneously is mathematically challenging. The coupling between trajectory variables and transmission power yields a highly non-convex optimization problem, which complicates the design of efficient algorithms [7–10]. Conventional convex optimization-based approaches, such as Successive Convex Approximation (SCA), have been widely adopted to address these issues [5, 6]. While effective to some extent, these methods typically rely on relaxations or approximations that may not fully capture mobility and energy constraints, and their scalability becomes limited as system complexity increases [11–13].

To overcome these limitations, metaheuristic algorithms have emerged as promising alternatives owing to their global search capability and flexibility in handling non-convex problems [14–16]. Among them, the Bat Algorithm (BAT), inspired by the echolocation mechanism of bats, provides an effective balance between exploration and exploitation and has shown strong potential in wireless optimization tasks [17, 18]. Motivated by these advantages, this work adopts BAT for the joint optimization of UAV trajectory and power allocation in UAV-assisted relay systems.

The main contributions of this paper are summarized as follows:

- 1) We formulate a joint UAV trajectory and power allocation optimization problem for Amplify-and-Forward (AF) UAV relaying, which results in a highly non-convex and tightly coupled optimization problem.
- 2) We propose a unified joint optimization framework that enables the simultaneous adaptation of UAV trajectory and transmit power under practical communication constraints.
- 3) A Bat Algorithm (BAT)-based metaheuristic is developed to solve the resulting problem, where a standard penalty-based constraint handling technique is incorporated to ensure solution feasibility.
- 4) Simulation results demonstrate that the proposed framework achieves higher achievable rates while

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maintaining competitive stability compared with benchmark convex optimization-based methods.

The remainder of the paper is organized as follows. Section II reviews related works. Section III presents the system model and formulates the optimization problem. Section IV describes the proposed BAT-based solution framework. Section V provides simulation results and performance analysis. Section VI concludes the paper.

II. RELATED WORK

The optimization of UAV-assisted communications has attracted significant research attention. Early foundational studies, such as those by Zhan *et al.* [4] investigated UAV relay communications under various deployment scenarios. Building on this, Zeng *et al.* [3] provided a comprehensive survey of UAV communications, highlighting the opportunities and challenges in the field.

A major focus in recent literature has been the joint design of trajectory and resource allocation. Jiang *et al.* [5] formulated the throughput maximization problem for UAV relaying, while Wu *et al.* [6] addressed joint trajectory and transmit power optimization specifically under malicious jamming scenarios. Further extending this domain, Nasrollahi and Mirrezaei [7] demonstrated that co-designing the trajectory and power significantly improves throughput compared to static designs. More complex scenarios have also been investigated; for instance, Yu *et al.* [8] studied UAV relays with wireless power transfer, and Duo *et al.* [9] proposed robust strategies for probabilistic LoS environments. Additionally, Trang *et al.* [10] focused on UAV speed control to ensure transmission quality.

The importance of trajectory and power co-design is further highlighted in [11–13]. However, to handle the inherent non-convexity of these problems without relying on extensive relaxations, metaheuristics with constraint-handling techniques have been applied [14–16]. While many prior studies have utilized algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), or Gravitational Search Algorithms (GSA) [17], this paper adopts the Bat Algorithm (BAT) [18, 19] due to its superior balance between exploration and exploitation.

III. SYSTEM MODEL AND PROBLEM FORMULATION

The system model is illustrated in Fig. 1. We consider a UAV-assisted relay network consisting of a ground source node (S), a UAV relay (R), and a ground destination node (D). Both S and D are located at fixed positions on the ground, while the UAV operates at a constant altitude h . Due to severe obstruction or excessive separation between S and D, a direct communication link is assumed to be unavailable. Therefore, the UAV serves as an aerial intermediary to facilitate data transmission between the two nodes. For simplicity, detailed UAV dynamics such as acceleration limits and propulsion energy consumption are not explicitly considered in this work.

Without loss of generality, a Cartesian coordinate system is adopted in which S and D are placed at $(0,0,0)$ and $(L,0,0)$, respectively. The UAV acts as an Amplify-

and-Forward (AF) mobile relay and flies within a given time interval T . Its time-varying position at time $t \in (0, T)$ is thus denoted by $(x(t), y(t), h)$. The UAV's initial and final positions are predetermined as (x_0, y_0, h) and (x_F, y_F, h) , respectively. The minimum required traveling distance for the UAV is given by:

$$d_{\min} = \sqrt{(x_F - x_0)^2 + (y_F - y_0)^2} \quad (1)$$

Let V_{\max} be the UAV's maximum allowable speed. To guarantee the existence of at least one feasible trajectory, the condition $d_{\min} \leq V_{\max}T$ must hold.

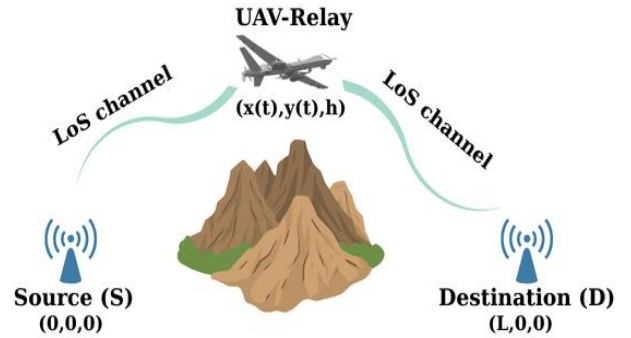


Fig. 1. The system model.

For analytical tractability, the total flight time T is uniformly divided into N time slots, each with a duration $\tau = \frac{T}{N}$. A sufficiently large N ensures that the UAV's position can be approximated as static within each time slot. Consequently, the UAV trajectory is represented by a $2 \times N$ matrix:

$$\mathbf{Q} = \begin{bmatrix} x[1] & x[2] & \dots & x[N] \\ y[1] & y[2] & \dots & y[N] \end{bmatrix}. \quad (2)$$

which must satisfy the trajectory constraints described subsequently.

$$(x[n+1] - x[n])^2 + (y[n+1] - y[n])^2 \leq \left(\frac{VT}{N}\right)^2 \quad (3)$$

$$n = 1, 2, \dots, N-1.$$

here, V denotes the UAV's velocity.

Since LoS links primarily dominate the communication channels from S to R and from R to D, the channel power from S to R at slot n th follows the free-space path loss model [5, 8], expressed as:

$$h_{SR}[n] = \frac{\beta_0}{x^2[n] + y^2[n] + h^2} \quad (4)$$

$$h_{RD}[n] = \frac{\beta_0}{(x[n]-L)^2 + y^2[n] + h^2} \quad (5)$$

where β_0 denotes the channel power gain at the reference distance $d = 1$ meter, and its value depends on the carrier frequency and antenna gain.

Although a Line-of-Sight (LoS) channel with free-space path loss is assumed in this work, such a model is widely adopted in UAV-enabled communications, particularly when the UAV operates at a sufficient altitude and maintains a high probability of LoS links with ground nodes. This assumption provides a tractable yet

representative approximation for analyzing joint trajectory and power optimization. More realistic channel models incorporating probabilistic LoS/NLoS conditions or shadowing effects can be readily integrated into the proposed framework by appropriately modifying the channel gain expressions, without altering the underlying optimization strategy.

Let $x_S[n]$ be the signal transmitted by the source S at time slot n . The received signal at the UAV relay is expressed as:

$$y_R[n] = \sqrt{p_S[n]} h_{SR}[n] x_S[n] + z_1[n] \quad (6)$$

The UAV relay employs an Amplify-and-Forward (AF) strategy. To satisfy the relay transmit-power constraint $p_R[n]$, the relay amplification factor $\delta[n]$ is given by:

$$\delta[n] = \sqrt{\frac{p_R[n]}{p_S[n]|h_{SR}[n]|^2 + N_1}} \quad (7)$$

The signal at D is as follows:

$$\begin{aligned} y_D[n] &= \sqrt{p_R[n]h_{RD}[n]} y_R[n] + z_2[n] \\ &= \delta \sqrt{p_R[n]h_{RD}[n]p_S[n]h_{SR}[n]} x_S[n] + \\ &\quad \delta \sqrt{p_R[n]h_{RD}[n]} z_1[n] + z_2[n] \end{aligned} \quad (8)$$

here, $p_S[n]$ and $p_R[n]$ denote the transmit power by S and UAV-relay at slot n , and $z_1[n] \sim \mathcal{CN}(0, N_1)$, $z_2[n] \sim \mathcal{CN}(0, N_2)$ are additive white Gaussian noise (AWGN) at the R and D.

Accordingly, the instantaneous equivalent SNR at the destination is expressed as [5]:

$$\gamma[n] = \frac{p_S[n]p_R[n]h_{SR}[n]h_{RD}[n]}{p_S[n]h_{SR}[n]N_2 + p_R[n]h_{RD}[n]N_1 + N_1N_2} \quad (9)$$

The achievable transmission rate (bits/s/Hz) at time slot n is:

$$R[n] = \frac{1}{2} \log_2(1 + \gamma[n]) \quad (10)$$

Our objective is to maximize the end-to-end throughput from S to D by jointly optimizing the transmit powers of the source and the relay, as well as the UAV relay's trajectory. The optimization problem is formulated as follows:

$$(P:) \quad \max_{\substack{\{p_S[n], p_R[n]\}_{n=1}^N \\ \{x[n], y[n]\}_{n=1}^N}} \sum_{n=1}^N R[n] \quad (11)$$

$$s. t. \sum_{n=1}^N p_S[n] \leq N\bar{P}_S, \quad \sum_{n=1}^N p_R[n] \leq N\bar{P}_R \quad (12)$$

$$p_S[n] \geq 0, \quad p_R[n] \geq 0, n = 1, 2, \dots, N \quad (13)$$

$$(x[n+1] - x[n])^2 + (y[n+1] - y[n])^2 \leq \left(\frac{VT}{N}\right)^2 \quad (14)$$

$$n = 1, 2, \dots, N - 1$$

where \bar{P}_S and \bar{P}_R denote the maximum average transmit powers of the source and the UAV relay, respectively, for each time slot. Problem (P) is inherently non-convex due to the coupled relationship between the power variables

and the UAV trajectory variables, which makes the optimization highly challenging. To effectively address this issue, we adopt a constraint-handling technique integrated with the BAT algorithm to jointly determine the optimal power allocation and relay trajectory for problem (P). It is worth noting that, in the amplify-and-forward relaying model, the noise amplification at the UAV is inherently included in the end-to-end SNR expression used to compute the achievable rate.

IV. PROPOSED APPROACH

A. Bat Algorithm

The Bat Algorithm (BAT) is inspired by the echolocation behavior of bats, which balance exploration and exploitation using frequency, loudness, and pulse rate [18]. Each bat i represents a candidate solution with position x_i , velocity v_i , frequency f_i , loudness A_i , and pulse emission rate r_i . The frequency for bat i at iteration t is updated as:

$$f_i^{(t)} = f_{min} + (f_{max} - f_{min})\beta \quad (15)$$

where $\beta \sim U(0,1)$ is a random number, and $[f_{min}, f_{max}]$ defines the frequency range.

The velocity and position updates are given by:

$$v_i^{(t)} = v_i^{(t-1)} + (x_i^{(t-1)} - x_*^{(t-1)})f_i^{(t)} \quad (16)$$

$$x_i^{(t)} = x_i^{(t-1)} + v_i^{(t)} \quad (17)$$

where x_* denotes the global best solution at iteration $t-1$. For exploitation, with a probability $r_i^{(t)}$, a local solution is generated by:

$$x_{new} = x_* + \epsilon A_i^{(t)} \quad (18)$$

where $\epsilon \sim U(-1,1)$ is a random number. The loudness and pulse rate are updated as:

$$A_i^{(t+1)} = \alpha A_i^t \quad (19)$$

$$r_i^{(t+1)} = r_i^{(0)}(1 - e^{\rho t}) \quad (20)$$

$\alpha \in (0,1)$ and $\rho > 0$ are constants.

A new candidate solution $x_i^{(t)}$ is accepted if it improves the fitness and a random condition is satisfied:

$$(\text{rand} < A_i^{(t)} \wedge F(x_{new}) < F(x_i^{(t)})) \quad (21)$$

then set $x_i^{(t)} = x_{new}$.

B. Penalty-Based Constraint Handling

BAT is a metaheuristic optimization technique inspired by natural echolocation. Despite its effectiveness, BAT is inherently formulated for unconstrained optimization; therefore, applying it to constrained problems necessitates the incorporation of dedicated constraint-handling strategies to maintain solution feasibility and performance [20]. In this study, for the sake of simplicity, a penalty-based constraint-handling method is employed. We first convert the constrained optimization problem into an unconstrained one by introducing a penalty function. For a

candidate solution x (encoding UAV trajectory and power allocations), the penalized objective is defined as:

$$F(x) = f(x) + \sum_j r_j \max(0, g_j(x))^2 + \sum_k c_k h_k(x)^2 \quad (22)$$

where: $F(x)$ is the fitness function. r_j and c_k are positive weighting coefficients, referred to as penalty factors.

C. Optimize Power and Trajectory Algorithm

In this study, we propose a solution to the Problem (P) using a penalty function-based constraint handling technique. To limit the search domain, we convert the position of the UAV at time n ($x[n], y[n]$) in the Cartesian coordinate system to the polar coordinate system represented by the distance and angle from the origin. When the UAV moves with velocity V , the distance between two consecutive survey points is determined by $V \cdot t$. When the velocity of the UAV is constant, the optimal variable to be searched will be the drone's direction. Then the position of the UAV is determined by:

$$\begin{aligned} x[n] &= x[n-1] + D \cos(\theta[n]) \\ y[n] &= y[n-1] + D \sin(\theta[n]) \end{aligned} \quad (23)$$

with $D = V \cdot t$.

The direction-angle-based trajectory formulation offers a good trade-off between solution quality and computational complexity under practical mobility constraints.

So, the problem (P) is described as follows:

$$(P1): \max_{\substack{\{p_s[n], p_r[n]\}_{n=1}^N \\ \{\theta[n]\}_{n=1}^N}} \sum_{n=1}^N R[n] \quad (24)$$

$$0 \leq \theta[n] \leq 2\pi, n = 1, 2, 3, \dots, N-1.$$

Applying the constraint transformation technique to the Problem (P1), we have an unconstrained optimization problem as follows:

$$(P2): \min_{\substack{\{p_s[n], p_r[n]\}_{n=1}^N \\ \{\theta[n]\}_{n=1}^N}} \sum_{n=1}^N -R[n] \\ + c_1 \max\left(\sum_{i=1}^n p_s[i] - n\bar{P}_s, 0\right) \\ + c_2 \max\left(\sum_{i=1}^n p_r[i] - n\bar{P}_r, 0\right) \\ \text{s.t. } 0 < p_s[n] \leq \bar{P}_s; 0 < p_r[n] \leq \bar{P}_r; \\ 0 \leq \theta[n] \leq 2\pi, n = 1, 2, 3, \dots, N-1. \quad (25)$$

We develop an algorithm to solve problem (P2) based on the Bat Algorithm (BAT). Each agent in the population is represented by a vector $E = (\theta, p_s, p_r)$, which characterizes the UAV-relay system's position and transmission powers at time n . The optimal solution is searched over a population of M candidate vectors using BAT, where the parameters c_1 and c_2 are set to 0.02 based on empirical tuning to balance constraint satisfaction and

convergence stability. The complete procedure is summarized in Algorithm 1.

Algorithm 1. UAV Trajectory and Transmission Power Optimization

Input: Set the required parameters:

- $N \leftarrow$ Number of points in the flight duration
- $H \leftarrow$ Height of the UAV
- $\bar{P}_s, \bar{P}_r \leftarrow$ Maximum transmission power of S and R
- $(x_0, y_0), (x_N, y_N) \leftarrow$ Coordinates of the first and last UAV locations
- $M \leftarrow$ Number of agents
- $I_{max} \leftarrow$ Number of iterations

Output: Optimal UAV positions and transmission power $\{p_s[n], p_r[n], \theta[n]\}_{n=1}^N$

1. Calculate the initial transmission rate $R[1]$:
Compute the transmission rate at the first UAV location using Eq. (10).
 2. $n \leftarrow 1$
 3. WHILE $n < N$ DO
 4. Compute total transmit power at the S, R
 5. Compute total transmission rate.
 6. Initialize M agents with random (p_s, p_r, θ)
 7. $i \leftarrow 1$
 8. WHILE $i < I_{max}$ DO
 9. $k \leftarrow 1$
 10. WHILE $k < M$ DO
 11. Compute the objective of agent k using Eq. (25)
 12. Identify the best agent.
 13. Update the agent's position using Eq. (22).
 14. $k \leftarrow k + 1$
 15. END WHILE
 16. $i \leftarrow i + 1$
 17. END WHILE
 18. $(p_s[n+1], p_r[n+1], \theta[n+1])$ Best agent's position from the current iteration.
 19. Convert $\theta[n+1]$ to Cartesian coordinates $(x[n+1], y[n+1])$ using Eq. (22).
 20. $n \leftarrow n + 1$
 21. Compute the transmission rate $R[n]$ at the n -th UAV location using Eq. (10).
 22. END WHILE
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V. NUMERICAL RESULT AND DISCUSSION

In this section, simulation results are presented to demonstrate the effectiveness of the proposed BAT-based approach. Unless otherwise specified, the parameters are summarized in Table I. The UAV altitude is fixed at $h = 100$ m, and the mission duration is $T = 100$ s with $N = 50$ time slots. Results are averaged over 100 independent runs for statistical reliability.

TABLE I. THE SIMULATION PARAMETERS

Parameter	Value
UAV altitude (h)	100 (m)
Max UAV speed (Vmax)	50 (m/s)
Bandwidth	20 (MHz)
Noise spectral density	-100 (dBm/Hz).
Channel gain at reference	-30 (dBm)
Source power limit (P_s^{max})	10 (dBm)
Relay power limit (P_r^{max})	10 (dBm)
Time slots (N)	50

The main parameter settings of the Bat Algorithm used in the simulations are summarized in Table II.

TABLE II. BAT ALGORITHM PARAMETERS USED IN SIMULATIONS

Parameter	Value
Population size	100
Maximum iterations	500
Initial loudness	0.5
Initial pulse rate	0.5
Minimum frequency	0
Maximum frequency	2

A. Power Allocation Strategy

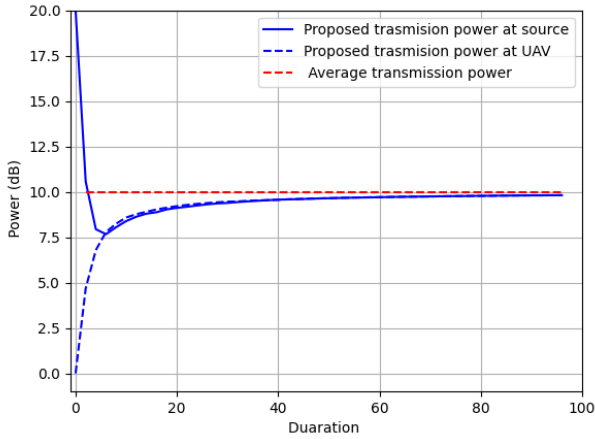


Fig. 2. Optimal source and relay power allocation profiles using the BAT algorithm.

Fig. 2 illustrates the optimal power allocations at the Source and UAV-relay in period $T = 100$ s. With the UAV flight trajectory according to the proposed algorithm, the transmit power at the source and at the UAV is always smaller than the average transmit power of each node.

B. Trajectory Optimization

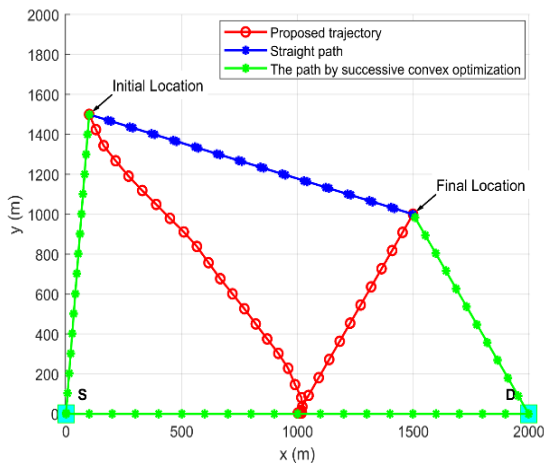


Fig. 3. Optimized UAV trajectories obtained by the proposed BAT algorithm and the baseline schemes.

Fig. 3 provides a top-down view of the optimal UAV trajectory generated by Algorithm 1, the straight flight trajectory, and the trajectory generated by the successive convex optimization algorithm over a flight period of $T = 100$ s. In the scenario initial and final positions are different,

the UAV does not follow a straight trajectory at a constant speed. Instead, it adjusts its flight path to maximize its mobility. Specifically, the first UAV moves toward the central position between S and D and hovers there to obtain the best channel conditions for energy reception and signal transmission in the real-time communication situation. Then, it moves toward the final destination, thereby enhancing the overall end-to-end throughput.

C. Throughput Performance

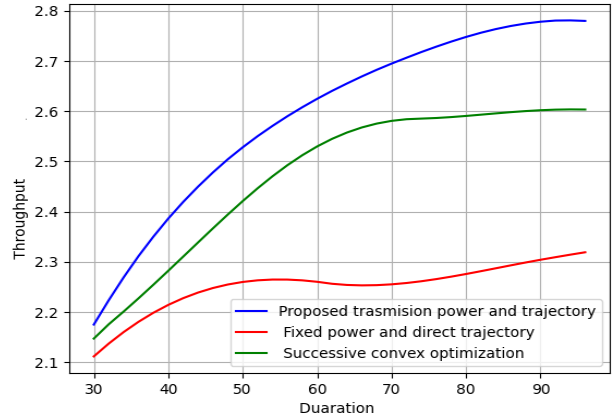


Fig. 4. Average system throughput (bits/Hz) achieved by the proposed BAT algorithm, SCA, and baseline schemes.

Fig. 4 demonstrates that BAT consistently outperforms the baseline schemes in terms of average throughput (measured in bits/Hz), achieving up to 25% gain over the solution obtained via convex optimization and 35% over the straight-line trajectory. These gains are attributed to the effective joint optimization of UAV trajectory and transmit power under non-convex constraints.

D. Convergence Behavior

Fig. 5 shows the convergence process of the objective function value according to the number of iterations. The curve shows that the objective function value decreases rapidly in the first 10 iterations, the objective function value decreases significantly, indicating that the algorithm has good optimization performance in the early stage. After about 20 iterations, the objective function value has almost no strong fluctuations or increases again, indicating that the algorithm has reached a state of convergence. This graph shows that the convergence process is fast and stable, proving that the algorithm has good optimization ability with a fairly fast convergence speed.

TABLE III. PERFORMANCE COMPARISON BETWEEN THE BAT AND SUCCESSIVE CONVEX OPTIMIZATION (SCA)

Metric	BAT Algorithm	SCA Algorithm
Average Best Objective	122.7670 bits/Hz	114.0990 bits/Hz
Stability	9.5366 bits/Hz	9.4690 bits/Hz
Execution Time	1.4286 s	1.3919 s

The performance comparison between the BAT and SCA algorithms is summarized in Table III. All results reported in Table III are obtained by averaging over 100 independent runs to ensure statistical reliability. The BAT

algorithm achieves a higher average achievable rate of 122.7670 bits/Hz compared to 114.0990 bits/Hz obtained by SCA, indicating superior solution quality in terms of throughput maximization.

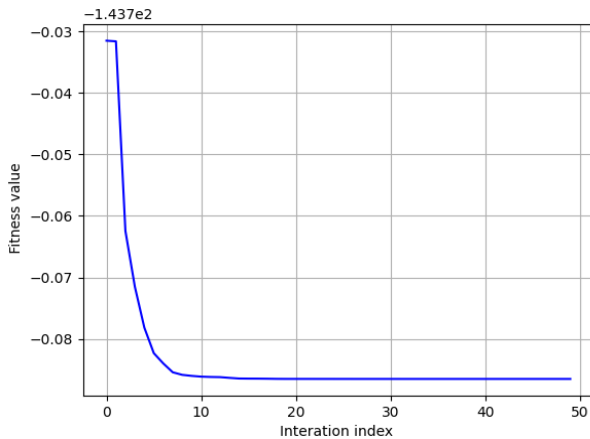


Fig. 5. Convergence of the proposed BAT-based optimization

The stability metric is defined as the standard deviation of the achievable rate over 100 independent runs and therefore shares the same unit as the throughput (bits/Hz). As shown in Table III, SCA exhibits slightly better stability, with a lower standard deviation (9.4690 bits/Hz) than BAT (9.5366 bits/Hz), reflecting more consistent performance across runs. In addition, SCA shows a marginally shorter execution time (1.3919 s versus 1.4286 s).

Overall, the results reveal a trade-off between achievable rate and performance consistency: BAT provides higher throughput, whereas SCA offers slightly improved stability and computational efficiency. Compared with conventional convex optimization and SCA-based approaches commonly adopted in prior studies, the proposed BAT-based framework highlights its distinctive capability in effectively handling the tightly coupled non-convex joint optimization of UAV trajectory and transmit power.

Regarding the sensitivity of the proposed Bat Algorithm, the optimization performance is mainly influenced by the balance between the loudness, the pulse rate, and the selected frequency range [18], whose values are determined as summarized in Table II. Qualitatively, the chosen configuration provides adequate exploration in the early iterations while enabling smooth trajectory refinement as the algorithm converges.

For constraint handling, the penalty factors are tuned to enforce the maximum transmit power constraints at the source and the UAV relay ($\overline{P}_s, \overline{P}_r$), as well as the UAV velocity (V_{max}) constraint. A qualitative sensitivity assessment indicates that, as long as the penalty values are sufficiently large to discourage constraint violations, the proposed framework consistently converges to feasible solutions and preserves stable throughput gains over the baseline methods. This suggests that the proposed approach is not overly sensitive to precise parameter tuning.

VI. CONCLUSION

This work studied the problem of joint trajectory and power optimization for UAV-assisted relay systems. To tackle the inherent non-convexity, we proposed a penalty-based metaheuristic framework combined with the Bat Algorithm (BAT). By adaptively balancing exploration and exploitation, BAT effectively optimized UAV trajectory and power allocation under mobility and power constraints. Simulation results confirmed that the proposed method achieves substantial throughput improvement, more efficient power distribution, and faster convergence than conventional convex optimization and baseline schemes. These results validate the suitability of BAT-based optimization for practical UAV communication scenarios in beyond-5G and 6G systems. Future research will extend this work to multi-UAV cooperation and hybrid learning-assisted metaheuristics.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Pham Thi Quynh Trang proposed an idea; Duong Thi Hang and Nguyen Viet Tuyen contributed to the simulation and analyzed the data; all authors had written the paper and approved the final version.

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