Directional Antenna-Assisted UAV Path Planning against Jamming Attacks

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***Abstract*—In recent years, unmanned aerial vehicles (UAVs) have been extensively studied as aerial base stations for wireless communication systems. In most previous studies, researchers have focused on optimizing UAV trajectories to maximize communication efficiency; however, the impact of intentional interference such as jamming has received comparatively little attention. In this paper, we propose a directional antenna-assisted UAV path planning method that simultaneously satisfies legitimate users' communication demands and mitigates the impact of jamming attacks. The UAV is equipped with a directional antenna whose coverage pattern varies with altitude and antenna gain, introducing a trade-off between communication efficiency and robustness against interference. To address this, we jointly optimize the UAV's hovering positions and antenna parameters using particle swarm optimization within user clusters formed by spatial clustering. Then we connect the obtained hovering points via a traveling salesman problem-based path construction to minimize the total flight distance. Through simulation experiments, we show that the proposed method effectively avoids jamming signals while ensuring successful data transmission for all users.**

***Index Terms*—Unmanned Aerial Vehicle, Directional Antenna, Particle Swarm Optimization, Flight Path Planning**

I. Introduction

In recent years, unmanned aerial vehicles (UAVs) have emerged as a promising technology for enhancing wireless communication systems. Because of their high mobility and rapid deployability, UAVs have been widely investigated for diverse applications, such as the establishment of temporary communication links in disaster-affected areas, provision of connectivity in regions with insufficient infrastructure, and data collection from Internet-of-Things devices. In particular, UAVs can act as aerial base stations that complement terrestrial networks, thereby improving service coverage and communication quality for ground users. Consequently, UAV-assisted communication has been recognized as a key enabler of next-generation wireless networks [1].

In a number of studies, researchers have focused on optimizing UAV positions and flight trajectories to efficiently provide communication services to ground users [2]. For instance, in several studies, researchers have determined the optimal three-dimensional placement of UAVs to maximize communication performance metrics such as the signal-to-interference-plus-noise ratio (SINR) or throughput, whereas others have dynamically adjusted the altitude and hovering positions according to the spatial distribution of users. In multi-UAV networks, cooperative trajectory design has also been explored to maximize coverage while mitigating mutual interference, and trajectory optimization problems have been formulated to account for time-varying user distributions. Overall, in these studies, the primary aim has been to use UAVs as efficient aerial communication resources that complement and extend terrestrial infrastructure.

However, in practical communication environments, UAVs may encounter not only legitimate users but also devices that emit jamming signals. Such interference can result from intentional jamming attacks aimed at disrupting communication or unintentional causes such as hardware malfunctions. Because UAV communication typically relies on line-of-sight propagation, radio signals tend to cover a wide area, which makes UAV systems particularly susceptible to external interference [3]–[5]. In particular, depending on the UAV's position, its communication footprint may become excessively large, which increases its likelihood of being affected by jamming signals and leads to degraded communication quality. Therefore, developing UAV communication designs that jointly ensure high efficiency and robustness against jamming has become a critical research issue.

One effective approach to mitigating jamming is to control the UAV's flight trajectory such that it operates within regions less affected by interference while maximizing the received signal power from ground users. Additionally, equipping the UAV with a directional antenna allows it to limit the reception direction and suppress unwanted signals that originate from jamming sources. Under such conditions, the determination of appropriate hovering positions becomes crucial because suboptimal positioning can significantly prolong the data collection time and degrade overall mission efficiency.

To address these challenges, we propose a directional antenna-assisted UAV path planning method that simultaneously satisfies the communication demands of ground users and mitigates the impact of jamming attacks. The proposed method first performs clustering based on the spatial distribution of ground users and then applies particle swarm optimization (PSO) to jointly determine the optimal hovering positions and antenna parameters while avoiding interference. Furthermore, the visiting sequence of the identified hovering points is optimized using a traveling salesman problem (TSP)-based approach, which results in an efficient flight trajectory that minimizes the total flight distance and ensures rapid mission completion. Through simulation experiments, we demonstrate that the proposed method effectively avoids jamming signals while ensuring reliable data transmission for all users.

II. System Model

In this study, we consider a communication system in which a single UAV equipped with a directional antenna delivers data to multiple ground users distributed over a target area. Figure 1 illustrates the conceptual structure of the system. On the ground, there exist N legitimate users and J jammers, and we assume that their locations are known in advance. Let $\mathcal{N}$ and $\mathcal{J}$ denote the sets of users and jammers, respectively. The position of each user $n \in \mathcal{N}$ is represented by the coordinate $\boldsymbol{p}_n = (x_n, y_n, 0)$ within target area A on the ground plane ($z = 0$). The position of each jammer $j \in \mathcal{J}$ is denoted by $\boldsymbol{p}_j = (x_j, y_j, 0)$. We assume that the locations of jammers are estimated in advance through prior measurement or environmental monitoring. The UAV communicates with ground users while hovering at multiple positions within a given altitude range and transmits data to users located within its communication coverage during each hovering period.

The communication between the UAV and ground users is defined as an air-to-ground uplink. Each ground user transmits data to the UAV, which is equipped with a downward-facing directional antenna to receive the uplink signals. The antenna radiation intensity pattern of the UAV, denoted by $U(\theta)$, is modeled as a function of the elevation angle θ as follows [6]:

$$U(\theta) = G_R \cdot \frac{\xi + 1}{2\pi} \cdot |\cos^{\xi}(\theta)|, \tag{1}$$

where G_R represents the maximum receive gain of the UAV antenna and ξ is the directivity index, which indicates the sharpness of the antenna beam. The larger ξ, the narrower the main lobe and the higher the directivity.

Based on the free-space path loss model [7], the received power P_R^{UAV} at the UAV from a ground user n is expressed as

$$P_R^{\mathrm{UAV}} = \frac{P_T U(\theta) \lambda^2}{4\pi d_n^2}, \tag{2}$$

where P_T is the transmit power of the ground user, λ is the carrier wavelength, and d_n is the distance between the UAV and user n. If the received power falls below a threshold $P_{\min}$, the communication link is considered to be unavailable. Accordingly, the maximum communication distance at elevation angle θ is given by

$$d_{\max}(\theta) = \sqrt{\frac{P_T U(\theta) \lambda^2}{4\pi P_{\min}}}. \tag{3}$$

Higher transmit power or larger receive gain extends the communication range, whereas stronger directivity limits the coverage area on the ground because of the narrower beam.

Figure 2 illustrates the three-dimensional communication coverage area of a UAV hovering at an altitude of 200 m. A comparison of the cases for directivity indices $\xi = 4$ and 20 demonstrates that as ξ increases, the antenna beam becomes narrower and the coverage area becomes more localized. Figure 3 shows a top-view cross-sectional projection of the communication area onto the ground plane ($z = 0$) for

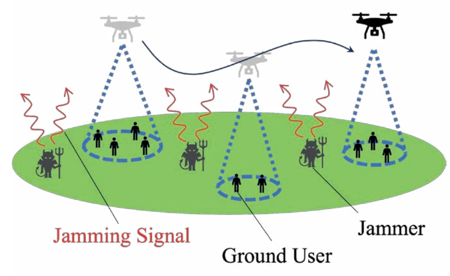
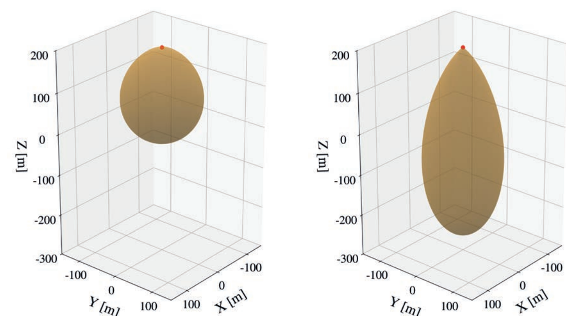


Fig. 1: System model



(a) $\xi = 4$ (b) $\xi = 20$

Fig. 2: Directional patterns

$\xi = 20$. The UAV's communication coverage on the ground is represented as a circular region with radius r. In this paper, ground users and jammers located within this circular area are considered to be covered by the UAV.

III. Proposed Method

A. Overview

In the proposed method, the UAV determines its hovering positions so that it avoids the influence of jamming signals. First, ground users are grouped through a clustering process and then PSO is applied to each cluster to determine the optimal hovering points for the UAV. Subsequently, the obtained hovering points are used to construct the UAV's flight trajectory, which is formulated as a TSP. This approach enables the UAV to establish an efficient flight route while minimizing the impact of jamming interference.

B. Clustering

In practical scenarios, ground users are often distributed non-uniformly over a wide area, which makes it inefficient for a UAV to visit every user individually. To address this, the proposed method introduces a clustering process that groups spatially proximate users and identifies representative hovering points for the UAV. By performing clustering based on inter-user distances, the UAV's hovering locations can adapt to the spatial distribution of users. In dense user regions, smaller clusters are naturally formed, whereas in sparse areas, larger clusters are created, which reflects the underlying spatial characteristics of user distributions.

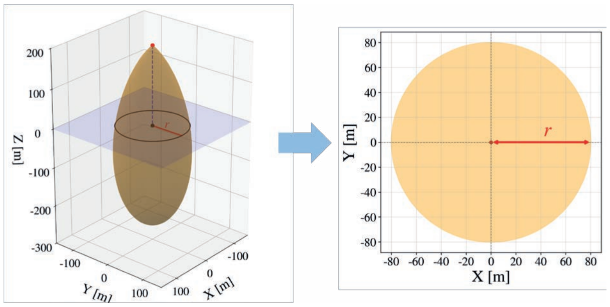


Fig. 3: Communication coverage area ($z = 0$)

Initially, each user $n \in \mathcal{N}$ is considered as an independent cluster. Specifically, for each user $n \in \mathcal{N}$, the corresponding cluster $\mathcal{C}_n$ is defined as

$$\mathcal{C}_n = \{n\}.$$

Subsequently, clusters that are spatially close to each other are iteratively merged. When two clusters $\mathcal{C}_n, \mathcal{C}_m$ are merged, the center of the resulting cluster, denoted by $\boldsymbol{c}_{n,m}$, is calculated as the centroid of all users within the merged set:

$$\boldsymbol{c}_{n,m} = \frac{1}{|\mathcal{C}_n \cup \mathcal{C}_m|} \sum_{l \in \mathcal{C}_n \cup \mathcal{C}_m} \boldsymbol{p}_l.$$

The cluster radius $\rho_{n,m}$ is defined as the maximum distance from the cluster center to any user within the cluster:

$$\rho_{n,m} = \max_{l \in \mathcal{C}_n \cup \mathcal{C}_m} \|\boldsymbol{p}_l - \boldsymbol{c}_{n,m}\|.$$

In this process, two clusters are merged only if the following condition is satisfied:

$$\rho_{n,m} \leq R_{\max},$$

where $R_{\max}$ denotes the maximum allowable cluster radius. The clustering procedure terminates when no further merging satisfies this condition for any pair of clusters.

C. Determination of Hovering Points

1) UAV Hovering Points: For each cluster $\mathcal{C}_k$ obtained from the clustering process, the objective is to determine the UAV's hovering position that maximizes communication efficiency while mitigating the impact of jamming signals.

In this study, the UAV is assumed to perform multiple hovering operations within each cluster. For cluster $\mathcal{C}_k$, the hovering points are denoted by

$$\mathcal{H}_k = \{\boldsymbol{h}_{k,1}, \boldsymbol{h}_{k,2}, \ldots, \boldsymbol{h}_{k,\mu_k}\},$$

where μ_k represents the number of hovering points assigned to cluster $\mathcal{C}_k$. The set of all hovering points across all clusters is expressed as

$$\mathcal{H} = \bigcup_{k=1}^{K} \mathcal{H}_k,$$

where K denotes the total number of clusters.

Accordingly, the problem can be formulated as the determination of the optimal hovering position of the UAV for the set $\mathcal{C}$ of users ($\mathcal{C} \subseteq \mathcal{N}$). The optimal hovering position $\boldsymbol{h}^*_{\mathcal{C}}$ is obtained by solving

$$\boldsymbol{h}^*_{\mathcal{C}} = \underset{\boldsymbol{h}}{\operatorname{argmax}} \; f_{\mathcal{C}}(\boldsymbol{h}), \tag{4}$$

where the objective function $f_{\mathcal{C}}(\boldsymbol{h})$ is defined as

$$f_{\mathcal{C}}(\boldsymbol{h}) = \alpha_{\mathcal{C}}(\boldsymbol{h}) + \beta_{\mathcal{C}}(\boldsymbol{h}). \tag{5}$$

Coverage efficiency $\alpha_{\mathcal{C}}(\boldsymbol{h})$ and communication quality $\beta_{\mathcal{C}}(\boldsymbol{h})$ are defined as follows:

- Coverage efficiency $\alpha_{\mathcal{C}}(\boldsymbol{h})$ represents the proportion of users in the set $\mathcal{C}$ whose communication quality exceeds a given SINR threshold φ when the UAV is hovering at position $\boldsymbol{h}$:

$$\alpha_{\mathcal{C}}(\boldsymbol{h}) = \frac{1}{|\mathcal{C}|} \sum_{n \in \mathcal{C}} \mathbb{1}(\text{SINR}(n, \boldsymbol{h}) > \varphi), \tag{6}$$

where $\mathbb{1}(\cdot)$ is the indicator function. The SINR is given by

$$\text{SINR}(n, \boldsymbol{h}) = \frac{P_R^{(n)}(\boldsymbol{h})}{I_J(\boldsymbol{h}) + N_0}, \tag{7}$$

where N_0 is the thermal noise power and $P_R^{(n)}(\boldsymbol{h})$ denotes the received signal power from user n:

$$P_R^{(n)}(\boldsymbol{h}) = \frac{U(\theta_n) G_R \lambda^2}{4\pi d_n^2}. \tag{8}$$

The total interference power caused by all jamming sources is expressed as

$$I_J(\boldsymbol{h}) = \sum_{j \in \mathcal{J}} P_R^{(j)}(\boldsymbol{h}). \tag{9}$$

- Communication quality $\beta_{\mathcal{C}}(\boldsymbol{h})$ represents the minimum normalized SINR among users that are successfully covered when the UAV is hovering at position $\boldsymbol{h}$:

$$\beta_{\mathcal{C}}(\boldsymbol{h}) = \min_{n \in \mathcal{C}_{\text{cover}}(\boldsymbol{h})} \frac{\text{SINR}(n, \boldsymbol{h})}{\Gamma}, \tag{10}$$

where the coverage set $\mathcal{C}_{\text{cover}}$ is

$$\mathcal{C}_{\text{cover}}(\boldsymbol{h}) = \{n \in \mathcal{C} \mid \text{SINR}(n, \boldsymbol{h}) > \varphi\},$$

and Γ is the normalization constant.

2) Derivation of Hovering Points Using PSO: To determine the set of hovering points $\mathcal{H}_k$ for each cluster $\mathcal{C}_k$, the proposed method uses PSO. The overall procedure of the proposed method is as follows:

Step 1. Set $\mathcal{C} := \mathcal{C}_k$, $\mu_k := 1$, and $\mathcal{W} := \emptyset$.

Step 2. Search for the UAV's optimal hovering position using PSO. Run PSO $T_{\max}$ times independently over the search space of $\boldsymbol{h}$ to optimize the objective function $f_{\mathcal{C}}(\boldsymbol{h})$. Select the position that maximizes

$f_{\mathcal{C}}(\boldsymbol{h})$ as $\boldsymbol{h}^*$ and assign it to $\boldsymbol{h}_{k,\mu_k}$.

Step 3. Update the set $\mathcal{W}$ of users currently covered by the UAV to $\mathcal{W} := \mathcal{W} \cup \mathcal{C}_{\text{cover}}(\boldsymbol{h}^*)$. If $\mathcal{W} = \mathcal{C}$, terminate the algorithm; otherwise, update $\mathcal{C} := \mathcal{C} \setminus \mathcal{C}_{\text{cover}}$ and $\mu_k := \mu_k + 1$, then return to Step 2.

Next, we explain how the hovering point for the user set $\mathcal{C}$ is determined by the PSO algorithm described in Step 2. First, L candidate solutions, referred to as particles, are initialized within the feasible search space. Each particle is defined as

$$\boldsymbol{h}^{(l)} = \left(x^{(l)}, y^{(l)}, z^{(l)}\right), \quad l = 1, 2, \ldots, L,$$

which represents a potential hovering position of the UAV in three-dimensional space. The search space for each coordinate is constrained by the cluster geometry and altitude limits as

$$x^{(l)} \in [c_{k,x} - \rho_k,\ c_{k,x} + \rho_k], \tag{11}$$

$$y^{(l)} \in [c_{k,y} - \rho_k,\ c_{k,y} + \rho_k], \tag{12}$$

$$z^{(l)} \in [h_{\min},\ h_{\max}], \tag{13}$$

where $\boldsymbol{c}_k = (c_{k,x}, c_{k,y})$ and ρ_k denote the center and radius of cluster $\mathcal{C}_k$, respectively. The fitness of each particle is evaluated using the cluster-specific objective function $f_{\mathcal{C}}(\boldsymbol{h}^{(l)})$.

The PSO algorithm iteratively updates the positions of particles based on both their individual experiences and those of the entire swarm. Let $\boldsymbol{h}^{(l)}(t)$ and $\boldsymbol{v}^{(l)}(t)$ denote the position and velocity of particle l at iteration t, respectively. Each particle maintains its personal-best position $\boldsymbol{q}_{\text{best}}^{(l)}$, whereas the best-performing particle in the swarm defines the global best $\boldsymbol{g}_{\text{best}}$. The PSO update equations are expressed as

$$\boldsymbol{v}^{(l)}(t+1) = \omega\, \boldsymbol{v}^{(l)}(t) + c_1 r_1(t)\left(\boldsymbol{q}_{\text{best}}^{(l)} - \boldsymbol{h}^{(l)}(t)\right) + c_2 r_2(t)\left(\boldsymbol{g}_{\text{best}} - \boldsymbol{h}^{(l)}(t)\right), \tag{14}$$

$$\boldsymbol{h}^{(l)}(t+1) = \boldsymbol{h}^{(l)}(t) + \boldsymbol{v}^{(l)}(t+1), \tag{15}$$

where ω is the inertia weight, c_1 and c_2 are the cognitive and social learning coefficients, respectively, and $r_1(t), r_2(t) \sim \mathcal{U}(0,1)$ are uniformly distributed random numbers. At each iteration, the fitness value $f_{\mathcal{C}}\left(\boldsymbol{h}^{(l)}(t)\right)$ is computed according to the objective function, and $\boldsymbol{q}_{\text{best}}^{(l)}$ and $\boldsymbol{g}_{\text{best}}$ are updated if improved fitness values are obtained. The algorithm continues until the maximum number of iterations $T_{\max}$ is reached. Finally, the optimal hovering point for cluster $\mathcal{C}$ is determined as

$$\boldsymbol{h}^* = \boldsymbol{g}_{\text{best}},$$

which represents the UAV's position that achieves the highest robustness against jamming while maximizing communication reliability for all users in the cluster.

D. Path Construction Between Hovering Points

Based on the obtained set of hovering points in $\mathcal{H}$, the proposed method determines the UAV's flight path by solving a shortest-path problem. Let $d(\boldsymbol{h}_i, \boldsymbol{h}_j)$ denote the travel distance between two hovering points. The objective is to find a path that allows the UAV to visit all hovering points exactly once and return to the starting point, which can be formulated as a TSP. To efficiently obtain a near-optimal solution with reduced computational complexity, the proposed method uses the 2-opt algorithm, which is a heuristic local search technique. By iteratively improving the visiting order of hovering points, 2-opt effectively shortens the total travel distance and constructs an efficient flight trajectory for the UAV.

TABLE I: Simulation parameter settings

Parameter	Description	Value
P_T	Transmit power of users and jammers (W)	0.5
G_R	Receive antenna gain of UAV	1.0
$P_{\min}$	Receiver sensitivity threshold (W)	1.0×10^{-8}
N_0	Thermal noise power (W)	8.0×10^{-14}
φ	SINR threshold	1.25×10^{5}
ξ	Antenna directivity index of UAV	20
N	Number of users	50
$h_{\min}$	Minimum UAV altitude (m)	10
$h_{\max}$	Maximum UAV altitude (m)	200
$T_{\max}$	Number of PSO iterations	100
L	Number of particles in PSO	100
ω	Inertia weight in PSO	0.1
c_1, c_2	Acceleration coefficients in PSO	1.5

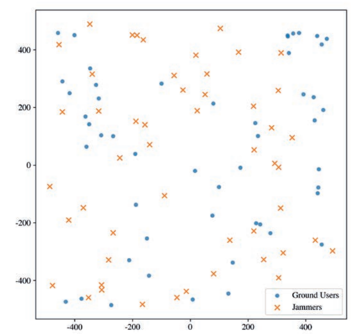


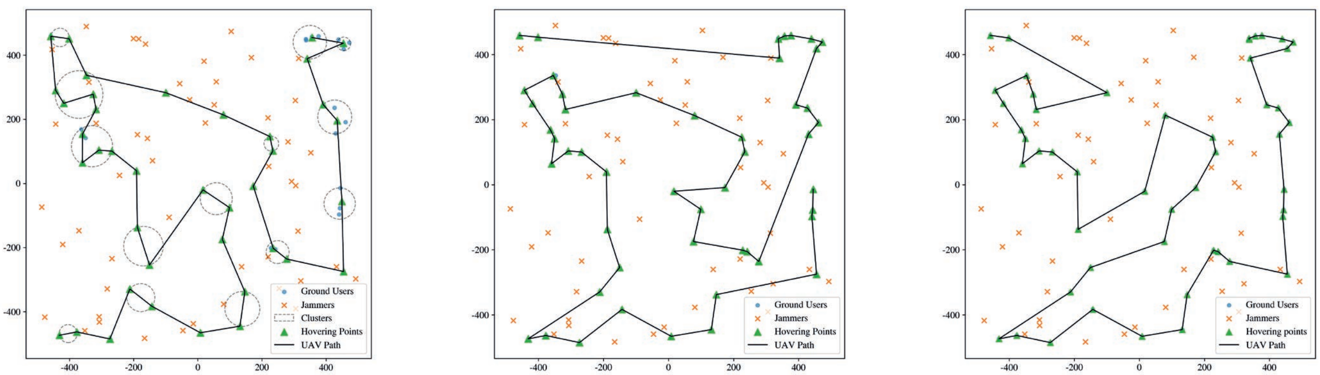
Fig. 4: Deployment of ground users and jammers.

IV. Performance Evaluation

A. Simulation Settings

To evaluate the effectiveness of the proposed method, simulation experiments were conducted. A target area $A = 500\ \text{m} \times 500\ \text{m}$ was considered, in which $N = 50$ ground users and $J \in \{20, 30, \ldots, 60\}$ jammers were randomly distributed (Fig. 4). To avoid unrealistic interference overlap, the placement of users and jammers was constrained such that the distance between any user and jammer was at least $20\ \text{m}$. The transmit power of each user and jammer was fixed at $P_T = 0.5\ \text{W}$. Each user was assumed to have a communication demand of $1\ \text{Mbits}$, and the communication process was regarded as complete when all users had received their required data volume. The UAV was allowed to fly within an altitude range between $h_{\min} = 10$ m and $h_{\max} = 200$ m during the hovering point search and flight operations.

A single UAV was deployed within area A, equipped with a downward-facing directional antenna modeled using (1). The



(a) Proposal (b) GPSO method (c) IND method

Fig. 5: Hovering point and flight path when $J = 50$

antenna directivity index ξ was set to 20 and the receive antenna gain was set to $G_R = 1$. The UAV performed data transmission only while hovering and all communication activities were suspended during movement between hovering points.

For the proposed method, the normalization constant Γ of the communication quality $\beta_{\mathcal{C}}(\boldsymbol{h})$ is set to

$$\Gamma = \frac{1}{N_0} \cdot \frac{P_T\, U(0)\, \lambda^2}{(4\pi h_{\min})^2}.$$

Moreover, in the proposed method, PSO was used to determine the optimal hovering points. The PSO parameters were set as follows: number of particles $L = 100$, number of iterations $T_{\max} = 100$, inertia weight $\omega = 0.1$, and acceleration coefficients $c_1 = c_2 = 1.5$.

The performance evaluation metrics are the total flight distance, total flight time, average hovering time, and total jamming duration.

- Total flight distance: the sum of the distances traveled by the UAV between all hovering points. This metric reflects the efficiency of the constructed flight path.
- Total flight time: the total time required for the UAV to complete the entire mission, including both flight and hovering durations.
- Total hovering time: the total duration that the UAV spends hovering at all positions to complete data transmission with the covered users.
- Total jamming duration: the cumulative time during which the UAV is affected by jamming signals while hovering or flying, which indicates the robustness of the proposed method against interference.

TABLE II: Simulation results when $J = 50$

Metrics	Proposal	GPSO	IND
Total flight distance	4841	5730	5749
Total time required	1236	1466	1474
Average hover time	19.2	18.2	18.0
Number of hovering points	39	49	50

For performance comparision, we show the results of GPSO (Global PSO) method and IND (Individual visiting) method.

GPSO method: In this method, the entire area A is defined as the search space of particles in PSO, and the hovering points are determined within this region. The objective function is identical to that of the proposed method. The optimization process is repeated until all users within area A are covered, and at each step, an optimal hovering point is determined and placed. If a hovering point obtained through optimization does not cover any new users, it is excluded from the final set of hovering points and not used in the path construction. The PSO parameters are set to be the same as those in the proposed method.

IND method: In this method, the UAV sequentially visits each user individually. Each hovering point is fixed directly above a user's position at the minimum allowable altitude, and the UAV performs communication with one user at a time. After completing data transmission with the current user, the UAV moves to the next user location and repeats the process until all users are served.

B. Evaluation Results

Table II shows the simulation results when the number of jammers is set to $J = 50$. The proposed method achieves

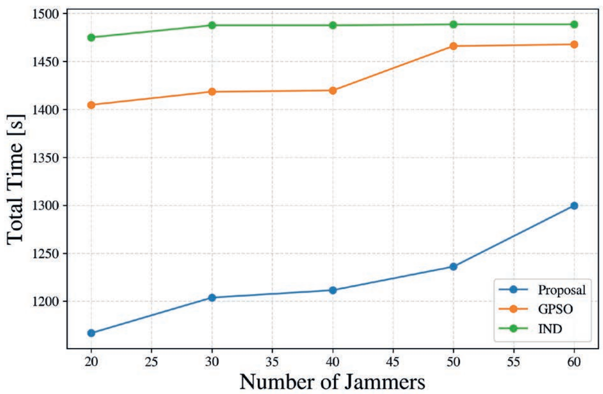


Fig. 6: Total flight time as a function of the number J of jammers

the shortest total flight distance and lowest total time required among all compared methods, which indicates that the UAV operates more efficiently under the proposed optimization strategy. In particular, the total flight distance is significantly reduced compared with GPSO and IND methods, which demonstrates that the proposed method successfully determines effective hovering points and constructs a compact trajectory that minimizes redundant movement. Although the average hovering time of the proposed method is slightly longer, the total number of hovering points is smaller, which implies that the UAV can communicate with multiple users simultaneously at well-selected positions. As a result, overall operation efficiency improves, and the proposed method achieves faster mission completion while maintaining reliable data transmission performance.

Figure 5 shows the UAV hovering positions and flight path obtained by each method. Figure 5(a) shows the result of the proposed method, where hovering points are efficiently placed to cover multiple users simultaneously while avoiding jammer regions. The trajectory forms a compact route that minimizes unnecessary movement. In contrast, Figure 5(b) shows the result of GPSO method, which produces a longer and more scattered flight path owing to less effective hovering-point selection. Figure 5(c) represents the flight path obtained by IND method, where the UAV visits each user sequentially at a low a altitude, resulting in the largest total flight distance and longest mission time.

Figure 6 shows the total mission time as a function of the number of jamming nodes J. As J increases, the total time required for all schemes gradually rises because the UAV must adjust its trajectory and communication parameters to avoid regions with stronger interference. The proposed method consistently achieves the shortest mission time across all values of J. This originates from the design of the objective function, which explicitly maximizes the user coverage ratio while minimizing exposure to jamming signals. Consequently, even under severe interference conditions with a large number of jammers, the UAV can maintain simultaneous communication with multiple users during each hovering period by adaptively selecting optimal hovering altitudes. In contrast, the GPSO and IND methods exhibit a significant increase in mission time as J increases, owing to inefficient hovering-point allocation and higher susceptibility to jamming. These results demonstrate that the proposed approach effectively suppresses the influence of jamming and sustains efficient data collection performance, thereby ensuring stable operation even in densely jammed environments.

V. Conclusion

This paper proposed a directional antenna-assisted UAV path planning method to achieve efficient and reliable data collection in the presence of jamming attacks. The proposed method jointly optimizes the UAV's hovering positions and antenna parameters using particle swarm optimization within user clusters formed by spatial clustering, and constructs an efficient flight path based on the traveling salesman problem. Through simulation experiments, it was confirmed that the proposed method achieves the shortest total flight distance and mission time compared with GPSO and IND methods.

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