Letter

Achieving Physical Layer Security Against Location Unknown Eavesdroppers via Friendly Jammer

Heng Zhang, Jianwei Sun, Xin Wang, and Chenglong Gong

Dear Editor,

This letter is concerning friendly jamming unmanned aerial vehicles (UAVs) to assist in the safe communication of UAV base stations. Due to the openness of UAV wireless communication, it is vulnerable to attacks leading to information disclosure or blockage. To address this issue, friendly jamming UAVs can assist UAV base stations and improve the security of wireless communications. This letter introduces a dual UAV system that consists of a source UAV (S-UAV) and a friendly jamming UAV (J-UAV). We construct an optimization problem to maximize the security region under physical constraints, which is non-convex and complicated. Security region (SR) is proposed for assessing the security performance of the whole system. Numerical simulations show that the hazard level of unknown eavesdroppers is attenuated after trajectory and power optimization.

Since ancient times, human beings have created countless autonomous intelligent systems (AISs). In recent decades, AISs have reached a higher level due to the rapid development of artificial intelligence [1]. Among them, AISs represented by UAVs have been widely used in various fields [2]. However, the communication security of UAVs has always been a concern because of the inherent broadcast characteristics of wireless media transmitted by UAVs. Many scholars have made a great deal of work on the communication security of UAVs [3]–[6]. For example, the mobility deployment and robust connectivity of UAVs were exploited to improve the reliability of wireless transmission systems [7]. In the application of UAVs as relay and base stations, scholars have also proposed various methods to solve problems such as the control of position and power [8]. In [9], an efficient greedy algorithm was investigated to determine the position of deployed UAVs in a predefined area.

In recent years, the concept of friendly jamming UAVs has been introduced into the study of communication security [10]. Zhou *et al*. considered a mobile UAV as a source station instead of a fixed one and jointly optimized the trajectories and power of the mobile base station and the jamming UAV [11]. Motivated by the above mentioned works, we consider a dual UAV communication model. Distinguishing from a fixed ground base station, we treat one UAV as an airborne mobile base station and the other as a friendly jammer to assist the legitimate communication between the base station and the user. We investigate the influence of friendly jamming UAV three-dimensional deployment and power on the communication security of mobile UAV base stations. An iterative algorithm is proposed, and its effectiveness is verified by numerical simulation.

System model and problem formulation: As shown in Fig. 1, the entire communication system has four nodes: S-UAV, J-UAV, ground users (Bob), and eavesdroppers (Eves). S-UAV flies on a predetermined trajectory and sends confidential information to Bob. At the same time, Eves at unknown locations also receive legitimate information. J-UAV emits artificial noise to reduce the probability of Eves receiving the signal.

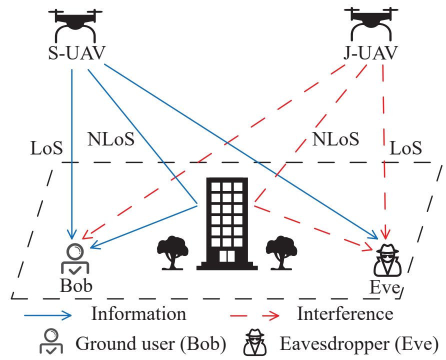

Fig. 1. The dual UAV mobile system model.

Air-to-ground transmissions between UAVs and ground receivers can be divided into line of sight (LoS) propagation and non-light of sight (NLoS) propagation. The probabilities of LoS transmission are given by [12]

$$P_{\rm LoS}=\frac{1}{1+\phi\exp[-\varphi(\alpha_k-\phi)]},\ k\in\{s,j\} \tag{1}$$

where $\alpha_k=\arctan(\frac{h_k}{r_{k,u}})$ is the UAVs elevation angle, $r_{k,u}$ is the distance between the ground users and the projection of the UAVs in the ground plane, and ϕ and φ are the environmental constants.

The average path loss between UAVs and ground users is given by

$$\bar{L}_{k,u}=P_{\rm LoS}\left|d_{k,u}\right|^{\beta_L}\eta_{\rm LoS}+P_{\rm NLoS}\left|d_{k,u}\right|^{\beta_N}\eta_{\rm NLoS]} \tag{2}$$

where $P_{\rm LoS}=1-P_{\rm NLoS}$. It can be seen from (2) that $\bar{L}_{k,u}$ is a strictly distance related quantity. Based on the above ground-air channel model and the definition of signal-to-noise ratios (SNRs), we obtain the instantaneous SNRs of users and eavesdroppers as

$$\gamma_b=\frac{P_s/\bar{L}_{s,b}}{P_j/\bar{L}_{j,b}+\sigma_b^2},\ \ \gamma_e=\frac{P_s/\bar{L}_{s,e}}{P_j/\bar{L}_{j,e}+\sigma_e^2} \tag{3}$$

where P_s and P_j denote the power of S-UAV and J-UAV, respectively, σ_b^2 and σ_e^2 are the noise powers at Bob and Eves.

In practice, J-UAV will attempt to disturb all possible eavesdroppers while ensuring communication for legitimate users. In a given area, we assume that all possible eavesdroppers are evenly distributed, and the locations of potential unknown eavesdroppers are within the set w_e. On the premise of $\gamma_b>\bar{\gamma}_b$, if the SNR of an eavesdropper at a location satisfies $\gamma_e<\bar{\gamma}_e$, the location is defined as a security location. Note that $\bar{\gamma}_b$ and $\bar{\gamma}_e$ are manually set SNR thresholds for the user and the eavesdropper, respectively. The set of all security locations is SR.

The locations of unknown eavesdroppers are random in the given area. We assume a series of discrete eavesdropper positions within the target area and count the total number of SR. The formula for SR can be expressed as

$$\Delta=\sum_{e\in w_e}\delta_e \tag{4}$$

where δ_e is an indicative function, i.e., $\delta_e=1$ when $\gamma_e<\bar{\gamma}_e$ and $\delta_e=0$ otherwise.

Under the constraints of power, speed, and altitude, the 3D location, and power of J-UAV are optimized to maximize SR. For a given set w_e and S-UAV of different positions and power, we formulated the optimization problem as

$$\max_{q_s,q_j,P_s,P_j,h_s,h_j,\delta_e}\sum_{e\in w_e}\delta_e \tag{5a}$$

$$\text{s.t.}\quad \gamma_b(q_s,q_j,h_s,h_j,P_s,P_j)\geq\bar{\gamma}_b \tag{5b}$$

$$\gamma_e(q_s,q_j,h_s,h_j,P_s,P_j)\leq\bar{\gamma}_e,\ \forall e\in\omega_e \tag{5c}$$

Corresponding author: Heng Zhang.

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H. Zhang is with the School of Computer Engineering, Jiangsu Ocean University, Lianyungang 222000, China (e-mail: ezhangheng@gmail.com).

J. W. Sun and C. L. Gong are with the School of Electronic Engineering, Jiangsu Ocean University, Lianyungang 222000, China (e-mail: jwei_sun@outlook.com; GongCL126@126.com).

X. Wang is with Shandong Provincial Key Laboratory of Computer Networks, Shandong Computer Science Center, Qilu University of Technology, Jinan 250014, China (e-mail: xinw.zju@gmail.com).

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$$q_{s,\min} \le q_s \le q_{s,\max} \tag{5d}$$

$$q_{j,\min} \le q_j \le q_{j,\max} \tag{5e}$$

$$h_{s,\min} \le h_s \le h_{s,\max} \tag{5f}$$

$$h_{j,\min} \le h_j \le h_{j,\max} \tag{5g}$$

$$P_{s,\min} \le P_s \le P_{s,\max} \tag{5h}$$

$$P_{j,\min} \le P_j \le P_{j,\max} \tag{5i}$$

$$\delta_e \in \{0,1\} \tag{5j}$$

where the positions of S-UAV and J-UAV are denoted by $q_s = (x_s, y_s)$ and $q_j = (x_j, y_j)$, respectively. The variables $q_{s,\min}$, $q_{s,\max}$, $q_{j,\min}$, $q_{j,\max}$, $h_{s,\min}$, and $h_{s,\max}$ are the constraints of the 3D locations within the target region. P_s and h_s respectively represent the power and altitude. It is noted that all parameters involved in S-UAV change with time, and the parameters of J-UAV will change with the variation of the parameters of S-UAV.

Optimization of flight trajectory and power: In order to optimize the 3D location and power of the J-UAV, a new iterative algorithm is proposed. Suppose that S-UAV flies within a period T and divide it into M time slots. The position of S-UAV at time m is given by $q_s[m] = (x_s[m], y_s[m])$. We optimize the J-UAV parameters on the basis of fixed S-UAV parameters. The optimization problem of J-UAV is divided into three sub-problems including two-dimensional position, noise emission power and flight altitude.

When considering the two-dimensional position subproblem, we fix the other two variables and consider only the effect of location change on the wireless network. By substituting (3) into the constraints (5b) and (5c), we obtain the following constraint in terms of path losses $\bar{L}_{j,b}$ and $\bar{L}_{j,e}$ given by

$$\bar{L}_{j,b} \ge \frac{P_j}{P_s/\bar{L}_{s,b}\bar{\gamma}_b - \sigma_b^2} = \frac{P_j}{\sigma_b^2(\frac{\bar{\gamma}_{s,b}}{\bar{\gamma}_b} - 1)} \tag{6}$$

$$\bar{L}_{j,e} \le \frac{P_j}{P_s/\bar{L}_{s,e}\bar{\gamma}_e - \sigma_e^2} = \frac{P_j}{\sigma_e^2(\frac{\bar{\gamma}_{s,e}}{\bar{\gamma}_e} - 1)} \tag{7}$$

where $\bar{\gamma}_{s,b} = P_s/\bar{L}_{s,b}\sigma_b^2$ and $\bar{\gamma}_{s,e} = P_s/\bar{L}_{s,e}\sigma_e^2$ are the average SNRs of Bob and Eve, respectively. Further analysis of 2D coordinate problems shows that the average path loss $\bar{L}_{j,u}$ defined by (2) is only a function of radius $r_{j,u}$, $u \in \{b, e\}$. The variable $\bar{L}_{j,u}$ monotonously increases as the radius $r_{j,u}$ increases. Then, we convert the constraints (6) and (7) to

$$(x_j - x_b)^2 + (y_j - y_b)^2 \ge R_b(P_j, h_j)^2 \tag{8a}$$

$$(x_j - x_e)^2 + (y_j - y_e)^2 \le R_e(P_j, h_j)^2 \tag{8b}$$

where

$$R_b(P_j, h_j) = r_{j,b}\Big|_{\bar{L}_{j,b}(P_j,h_j)=\frac{P_j}{\sigma_b^2(\frac{\bar{\gamma}_{s,b}}{\bar{\gamma}_b}-1)}} \tag{8c}$$

and

$$R_e(P_j, h_j) = r_{j,e}\Big|_{\bar{L}_{j,e}(P_j,h_j)=\frac{P_j}{\sigma_e^2(\frac{\bar{\gamma}_{s,e}}{\bar{\gamma}_e}-1)}}. \tag{8d}$$

Variables R_b and R_e are functions related to P_j and h_j. In (8c), $\bar{L}_{j,b}(P_j, h_j) = P_j/\sigma_b^2(\frac{\bar{\gamma}_{s,b}}{\bar{\gamma}_b} - 1)$ is the premise of $R_b(P_j, h_j) = r_{j,b}$, so is (8d). Based on (8a) and (8b), (5) can be rewritten as

$$\max_{x_j,y_j,\delta_e} \sum_{e\in w_e} \delta_e \tag{9a}$$

$$\text{s.t.} \quad (x_j - x_b)^2 + (y_j - y_b)^2 \ge R_b(P_j, h_j)^2 \tag{9b}$$

$$(x_j - x_e)^2 + (y_j - y_e)^2 \le R_e(P_j, h_j)^2 \tag{9c}$$

$$q_{j,\min} \le q_j \le q_{j,\max} \tag{9d}$$

$$\delta_e \in \{0,1\}. \tag{9e}$$

From (9d), the 2D position of J-UAV is restricted to a specific area. It can be seen from constraint (9b) that the feasible area for J-UAV is on or outside the circle with Bob as the center, as shown in Fig. 2. The feasible area ensures that (9b) is satisfied, and then we can further simplify the problem as

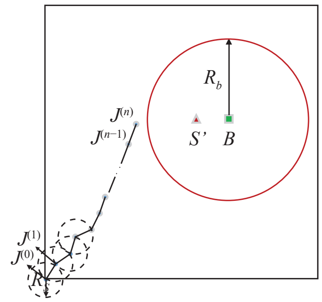

Fig. 2. Search coordinates of J-UAV trajectory.

$$\max_{x_j,y_j,\delta_e} \sum_{e\in w_e} \delta_e$$

$$\text{s.t.} \quad (x_j - x_e)^2 + (y_j - y_e)^2 \le R_e(P_j, h_j)^2$$

$$q_{j,\min} \le q_j \le q_{j,\max}$$

$$\delta_e \in \{0,1\}. \tag{10}$$

Assuming that the initial J-UAV position is at the origin, we follow a certain step R_s to find the position with the maximum SR. This position is used as the center of the circle for the next search step, and the previous operation is repeated until the end of the SR value does not change. A backtracking method can be applied to select the appropriate step size.

In the power subproblem, we optimize the power of J-UAV by assuming that the 3D coordinates (x_j, y_j, h_j) have been determined. We can rewrite (5) as

$$\max_{P_j,\delta_e} \sum_{e\in w_e} \delta_e \tag{11a}$$

$$\text{s.t.} \quad P_j \le \bar{L}_{j,b}\sigma_b^2(\frac{\bar{\gamma}_{s,b}}{\bar{\gamma}_b} - 1) \tag{11b}$$

$$P_j \ge \bar{L}_{j,e}\sigma_e^2(\frac{\bar{\gamma}_{s,e}}{\bar{\gamma}_e} - 1) \tag{11c}$$

$$\delta_e \in \{0,1\}. \tag{11d}$$

The above problem is a binary integer liner problem with linear constraints. From (11c), it can be seen that the objective function and P_j are positively correlated. Due to monotonicity, the optimal interference power satisfies the constraint (11b). Therefore, the solution of the UAV power subproblem is

$$P_j = \bar{L}_{j,b}\sigma_b^2(\frac{\bar{\gamma}_{s,b}}{\bar{\gamma}_b} - 1). \tag{12}$$

For the height subproblem, we assume that q_j and P_j are stationary, and the height of J-UAV h_j is to be optimized. In this case, the constraint (5b) takes an equal sign, i.e., $\gamma_b(h_j) = \bar{\gamma}_b$. The path loss $\bar{L}_{jb}(h_j)$ can be written as

$$\bar{L}_{j,b}(h_j) = \frac{P_j}{\sigma^2(\frac{\bar{\gamma}_{s,b}}{\bar{\gamma}_b} - 1)}. \tag{13}$$

According to (2), we notice that for a given 2D coordinate $q_j[m,n]$ of J-UAV, the path loss is related to only the height h_j and monotonic to it. Thus, the height satisfying the condition is derived as

$$h_j = \arg\max_{h_j} \Delta(h_j) : \bar{L}_{j,b}(h_j) = \frac{P_j}{\sigma^2\left(\frac{\bar{\gamma}_{s,b}}{\bar{\gamma}_b} - 1\right)}. \tag{14}$$

Based on the three subproblems solved previously, we summarized the double-layer cyclic network in Algorithm 1. We assign the 2D coordinates $q_s^{(0)}[0] = (x_s^{(0)}[0], y_s^{(0)}[0])$ of S-UAV and the altitude $h_j^{(0)}[0] = h_{j,\min}$ of J-UAV and $\Delta^{(0)}[0] = 0$. In a two-tier loop, the first layer loops the position of S-UAV. The trajectory of the S-UAV is a circle, and the departure position of S-UAV is $(0, 0)$. When $q_s^{(0)}[m] = q_s^{(0)}[0]$, it indicates that S-UAV has returned to the starting point and the cycle ends. When S-UAV is in the mth position, we provide a three-step iterative algorithm to optimize the 3D position and power of J-UAV. In the second loop, the following steps iterate n times: 1) When $n \ge 1$, $(x_j^{(n-1)}[0], y_j^{(n-1)}[0], P_j^{(n-1)}[0], h_j^{(n-1)}[0])$ in previous iterations are substituted into (10) to obtain $(x_j^{(n)}[0], y_j^{(n)}[0])$; 2)

Calculate the optimal power $P_j^{(n)}[0]$ according to (12) through the given $(x_j^{(n)}[0], y_j^{(n)}[0], h_j^{(n-1)}[0])$; 3) Substitute $(x_j^{(n)}[0], y_j^{(n)}[0], P_j^{(n)}[0])$ into (14) to obtain the altitude $h_j^{(n)}[0]$ of J-UAV. The updated parameter $\Delta^{(n)}[m]$ denotes the maximum SR of the nth location of J-UAV when S-UAV is in the mth slot.

Algorithm 1 Optimized Iterative Algorithm for J-UAV

Input : (x_b, y_b), h_s, P_s, (x_e, y_e);
Output : q_j, h_j, P_j;
Initialization: $q_s{}^{(0)}[0]$, $h_j{}^{(0)}[0]$, $\Delta^{(0)}[0] = 0$;
while $q_s{}^{(0)}[m] \neq q_s{}^{(0)}[0]$ **do**
  For $m \geq 1$, $q_s{}^{(0)}[0] \leftarrow q_s{}^{(0)}[m]$;
  if $\Delta^{(n)}[0] \neq \Delta^{(n-1)}[0]$ **then**
    $q_j{}^{(0)}[0] \leftarrow (0, 0)$;
    For $n \geq 1$, $q_j{}^{(n-1)}[0] \leftarrow q_j{}^{(n)}[0]$;
    $P_j{}^{(n-1)}[0] \leftarrow P_j{}^{n}[0]$;
    $h_j{}^{(n-1)}[0] \leftarrow h_j{}^{n}[0]$;
    Update $\Delta^{(n)}[0]$; $n = n + 1$;
  end if
  Update $\Delta^{(n)}[m]$; $m = m + 1$;
end while

Simulation results: In order to more accurately evaluate the security level of each location, we take into account a group of possible eavesdropper locations of size w_e = 10 000. These locations are evenly distributed within a square target area of 1 km × 1 km, where the parameters are $\phi = 9.61$, $\varphi = 0.16$, $\eta_{\text{LoS}} = 1$ dB, and $\eta_{\text{NLoS}} = 20$ dB. The path loss exponent for the air-to-ground links is set to $\beta = 2$. The source transmit power is $P_s = 27$ dBm and the noise powers are set to $\sigma_b^2 = \sigma_e^2 = -90$ dBm [10].

Fig. 3 shows the trajectories of J-UAV with different starting positions when Bob's position is fixed at (500, 500). The figure shows that the optimal position finally reached tends to be the same despite the different starting positions, which indicates that for J-UAV, its optimal 2D position depends on the relative positions of Bob and the source end when the J-UAV height and power are fixed.

Fig. 4 points out the relationship between the calculated optimal position at this time and the final SR percentage when calculating the two-dimensional coordinates with a step size of 5. SR proportion is the proportion of the number of secure locations in the whole target area. This figure shows that the value of the best SR obtained from different user positions tends to be the same in the final SR although the intermediate processes may vary.

Fig. 5 demonstrates the SNRs for all potential eavesdroppers in the target area. The final optimal position of J-UAV is around (250, 500). It can be seen that the closer the eavesdropper to J-UAV, the lower the value of γ_e, but not on the side close to the S-UAV and Bob. Therefore, the optimal location of the avesdropper should be both close to the J-UAV and far away from the S-UAV.

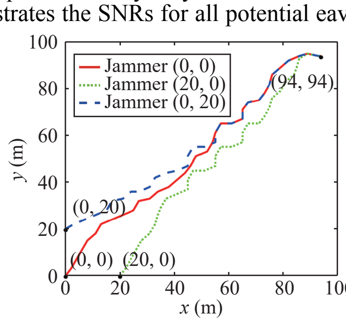

Fig. 3. Flight trajectory of different starting points of J-UAV.

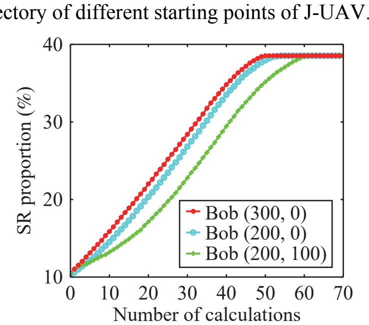

Fig. 4. SR proportion versus different Bob coordinates.

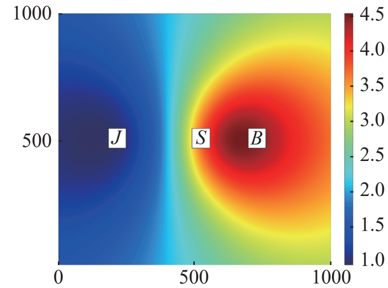

Fig. 5. γ_e for all possible Eve locations.

Conclusion: In this letter, we have investigated the use of friendly jamming UAVs to improve the performance of UAV communication networks. We have designed a new method for searching the optimal 3D coordinates and power for a mobile UAV base station scenario. This letter also proposes a new iterative algorithm making the SR maximized under the interference UAV location constraints. In future work, we will consider improving the attack strategy of eavesdroppers and finding a balance between eavesdroppers and friendly jammers.

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