UAV-Aided Secure Communications With Cooperative Jamming

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***Abstract*—This paper investigates unmanned aerial vehicle (UAV) enabled secure communication systems where a mobile UAV wishes to send confidential messages to multiple ground users. To improve the security performance, a cooperative UAV is additionally considered that transmits the jamming signal. In this system, we maximize the minimum secrecy rate among the ground users by jointly optimizing the trajectory and the transmit power of the UAVs as well as the user scheduling. To efficiently solve this nonconvex problem, we adopt block successive upper bound minimization techniques, which address a sequence of approximated convex problems for each block of variables. Numerical results verify that the proposed algorithm outperforms baseline methods.**

***Index Terms*—Unmanned aerial vehicle, trajectory optimization, physical layer security, cooperative jamming.**

I. Introduction

RECENTLY, unmanned aerial vehicle (UAV) techniques have been applied to wireless communication systems owing to their flexibility and cost-efficiency for network deployment [1]. For air-to-ground communications, UAVs could provide line-of-sight (LoS) channels, which results in the enhanced system capacity. These advantages lead to several researches on UAV-aided communication systems [2]–[19]. The authors in [2]–[4] studied placement optimization problems for mobile base stations (BSs) to improve wireless coverage of cellular networks, and [5] analyzed the performance of UAV-aided underlaying device-to-device systems. In [6], the average network delay was minimized by solving the cell partitioning problem, and the work in [7] optimized the direction of UAV for uplink systems. Trajectory optimization of mobile nodes has also been investigated in recent literature [8]–[19]. Especially, [8] considered UAV-enabled networks where multiple UAVs support downlink data transmission for several ground users in a time division multiple access (TDMA) manner. To maximize the minimum rate among the ground users, a joint optimization of user scheduling, power control, and trajectory was proposed in [8]. In addition, various trajectory optimization methods were presented for UAV relay networks [9]–[13], mobile ad hoc networks [14] [15], energy efficient UAV communications [16] [17], orthogonal frequency division multiple access systems [18], and mobile edge computing applications [19].

Meanwhile, physical layer security (PLS) has emerged as an important issue for wireless network designs [20]–[22]. There have been diverse studies on the PLS schemes for maximizing the secrecy rate in broadcast channels [21] and multiple access channels [22]. Cooperative jammers which transmit artificial noise on top of legitimate messages were shown to be an effective solution for the secure communication [23]–[26]. Nevertheless, when eavesdroppers are closely located to legitimate transmitters, it is still not easy to achieve meaningful secrecy rate performance with conventional PLS techniques.

To overcome this difficulty, several recent works applied the UAV methods to enhance the secrecy performance of wireless networks [27]–[29]. The authors in [27] examined power control algorithms for secure mobile relaying systems in the presence of a ground eavesdropper assuming that a relay moves along a fixed line path. It was shown in [27] that even when the trajectory of the mobile relay is not optimized, the secrecy rate performance is fairly enhanced compared to a static relay setup. Joint trajectory and transmit power optimization schemes were presented in [28] for a scenario where a ground eavesdropper tries to tap the information transmitted from a UAV to a legitimate ground receiver. A recent work [29] considered UAV-aided jamming methods to enhance the secrecy rate between a transmitter and a receiver fixed at the ground in the presence of a ground eavesdropper. However, the works in [28] and [29] cannot be directly extended to a general case with multiple legitimate users.

In this paper, we investigate secure UAV-aided communications where a mobile BS wants to secretly communicate with multiple legitimate ground users. To further improve the security performance, we consider an additional cooperative UAV which transmits the jamming signal. Due to the broadcast nature of radio frequency signals, messages intended to desired users can be leaked to unintended users, and thus private information for each user would be vulnerable to eavesdropping. Therefore, to support confidential data transmission, the message for each ground user should be kept secret from other users, as they may act as potential eavesdroppers [20], [21].

We adopt the TDMA protocol where at each time slot, the BS UAV sends confidential messages intended to one scheduled user while preventing unscheduled users from overhearing the message. To guarantee fairness among multiple ground users, the minimum secrecy rate maximization problem is addressed which jointly optimizes the trajectory and the transmit power of

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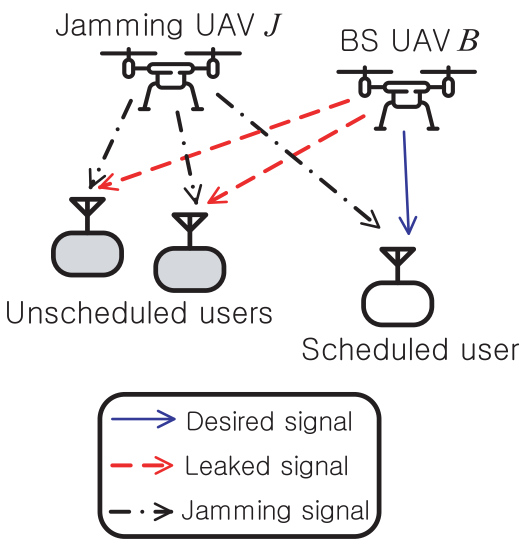

Fig. 1. System diagrams for UAV-aided secure communication systems.

the BS UAV and the jamming UAV as well as the user scheduling. Since we consider a general case with multiple ground users and the jamming UAV, the work in [28], which only maximizes the secrecy rate of a single legitimate user without a jammer, can be regarded as a special case of our problem. In addition, the proposed approach generalizes the results in [29] where a legitimate transmitter is located at a fixed position. Also, the trajectory optimization methods in [8] did not take the security issue into account, and thus it is difficult to apply the solution in [8] to our system model.

To efficiently solve the non-convex minimum secrecy rate maximization problem, we employ block successive upper bound minimization (BSUM) frameworks [30] which iteratively compute the user scheduling, the transmit power, and the trajectory of the UAVs by fixing other variables. The BSUM algorithm, which includes block coordinate descent and successive convex approximation methods as special cases, is a general framework for solving jointly non-convex problems. To find a solution for each variable, we successively solve approximated convex problems of the original non-convex one. Numerical results demonstrate that the proposed algorithm outperforms baseline schemes. It is also observed that the optimized trajectory of the BS and the jamming UAVs exhibit significantly different shape compared to the conventional method [8] without security consideration.

The paper is organized as follows: Section II explains the system model for the secure UAV communication networks and formulates the minimum secrecy rate maximization problem. In Section III, we propose an efficient algorithm for solving the minimum secrecy rate maximization problem based on the BSUM framework. The efficacy of the proposed optimization algorithm is demonstrated in Section IV through numerical results. Finally, the paper is terminated with conclusions in Section V.

II. System Model

In Fig. 1, we consider UAV-aided secure communications where a BS UAV B wishes to secretly transmit information to one of delay-tolerant K ground users with the help of a cooperative jamming UAV J. It is assumed that UAV $u \in \mathcal{U} \triangleq \{B, J\}$ periodically flies over the area of interest with period T[1] at the fixed altitude H_u. For simplicity, we ignore a collision event of two UAVs for the rest of the paper. For ease of analysis, we adopt a time-slotted system so that one time period T is divided into N time slots [8], [28]. The number of time slots N is assumed to be sufficiently large so that the continuous movement of the UAVs can be approximated.

To support downlink data transmission of multiple users, we employ the TDMA protocol in which the BS UAV sends the data intended to one scheduled user at each time slot. For secure communication, the message for the scheduled user should be kept secret from other unscheduled users [21]. Let $s_k[n] \in \{0, 1\}$ be a binary variable for user $k \in \mathcal{K} \triangleq \{1, \ldots, K\}$ at time slot $n \in \mathcal{N} \triangleq \{1, \ldots, N\}$ to indicate user scheduling, i.e., $s_k[n] = 1$ if user k is scheduled at time slot n and $s_k[n] = 0$ otherwise. Then, we have

$$s_k[n] \in \{0, 1\}, \quad \forall k, n, \tag{1}$$

$$\sum_{k\in\mathcal{K}} s_k[n] \leq 1, \quad \forall n. \tag{2}$$

For air-to-ground channels, we adopt a simple channel model [8], [9], [16]–[18] in which channel gains are dominated by the LoS links and the Doppler effect is well compensated. It has been reported in [31] that this LoS model is well matched with the measurement results for practical air-to-ground links. Then, the channel gain $h_{u,k}[n]$ between UAV u and user k at time slot n can be expressed as

$$h_{u,k}[n] = \frac{\rho_u}{H_u^2 + \|\mathbf{p}_u[n] - \mathbf{x}_k\|^2}, \quad \forall u, k, n, \tag{3}$$

where ρ_u denotes the reference pathloss of UAV u at 1 m, $\mathbf{p}_u[n] \in \mathbb{R}^{2\times 1}$ represents the horizontal coordinate of UAV u at time slot n, and $\mathbf{x}_k \in \mathbb{R}^{2\times 1}$ stands for the location of user k which is assumed to be fixed and is known to the UAVs by using the global positioning system and localization techniques.

The trajectory variable $\{\mathbf{p}_u[n]\}$ of UAV u is subject to the maximum speed constraint $V_{\max,u}$ as

$$\|\mathbf{p}_u[n+1] - \mathbf{p}_u[n]\| \leq V_{\max,u}\frac{T}{N}, \quad \forall u, n \in \mathcal{N}\backslash\{N\}. \tag{4}$$

Also, the UAVs have the following constraint [8]

$$\mathbf{p}_u[1] = \mathbf{p}_u[N], \quad \forall u, \tag{5}$$

which implies that the UAVs should go back to its starting position after one period to periodically support the users [8].[2]

Let $q_u[n]$ be the transmit power of UAV u at time slot n. For the power constraint at the UAV, we consider the average power $Q_{A,u}$ and the peak power budget $Q_{P,u}$ for UAV u. Then, it follows

$$\frac{1}{N}\sum_{n\in\mathcal{N}} q_u[n] \leq Q_{A,u}, \quad \forall u, \tag{6}$$

$$q_u[n] \leq Q_{P,u}, \quad \forall u, n. \tag{7}$$

[1] In practice, the UAVs would require energy supply or physical checkup periodically for maintaining communication services.

[2] With minor modifications, we can extend our system to a scenario where the starting position $\mathbf{p}_u[1]$ and the final position $\mathbf{p}_u[N]$ of the UAVs are predetermined in advance [9], [28].

When user k is scheduled for communicating with the BS UAV at time slot n, the secrecy rate $R_{S,k}[n]$ can be written as [25]

$$R_{S,k}[n] = \max\left\{R_k[n] - \max_{j\neq k} R_j[n], 0\right\}, \tag{8}$$

where the achievable data rate $R_k[n]$ at user k is given by

$$R_k[n] = \log\left(1 + \frac{h_{B,k}[n]q_B[n]}{\sigma^2 + h_{J,k}[n]q_J[n]}\right), \quad \forall k, n, \tag{9}$$

with σ^2 being the noise variance. In (9), we treat the signal from the jamming UAV as interference [23]. As a result, the achievable average secrecy rate $R_{S,k}$ at user k over N time slots can be expressed as

$$R_{S,k} = \frac{1}{N}\sum_{n\in\mathcal{N}} s_k[n]R_{S,k}[n]. \tag{10}$$

In this paper, we jointly optimize the user scheduling $\mathbf{S} \triangleq \{s_k[n], \forall k, n\}$, the transmit power at the UAVs $\mathbf{Q} \triangleq \{q_u[n], \forall u, n\}$, and the trajectory of the UAVs $\mathbf{P} \triangleq \{\mathbf{p}_u[n], \forall u, n\}$ so that the minimum average secrecy rate $R_{S,\min} \triangleq \min_{k\in\mathcal{K}} R_{S,k}$ among the ground users is maximized. The problem can be formulated as[3]

$$\text{(P)}: \max_{\mathbf{S},\mathbf{Q},\mathbf{P}} R_{S,\min} \tag{11}$$

$$\text{s.t. } (1),\ (2),\ (4)\text{–}(7). \tag{12}$$

In general, (P) is a non-convex problem due to the binary variable $\mathbf{S}$ and the non-convex objective function. Although the minimum rate maximization problem was solved in [8] for the UAV-aided communications, the solution cannot be directly applied to (P) because the objective is different and additional optimization variables for the jamming UAV are employed in our case. Also, note that [28] focused on a simple scenario where there are one legitimate ground user and one eavesdropper without a cooperative jammer, and thus the configuration in [28] can be viewed as a special case of (P) with $K = 2$, $s_1[n] = 1$, $s_2[n] = 0$, and $q_J[n] = 0, \forall n$. Furthermore, (P) boils down to the system model of [29] with a fixed BS UAV and a single ground user by setting $K = 2$, $s_1[n] = 1$, $s_2[n] = 0$, and $\mathbf{p}_B[n] = \mathbf{p}_B$, $\forall n$.

III. Proposed Algorithm

In this section, an efficient algorithm for solving (P) is proposed based on the BSUM framework [30] which iteratively identifies the user scheduling $\mathbf{S}$, the transmit power $\mathbf{Q}$, and the trajectory $\mathbf{P}$ by fixing other variables.

[3]The problem would be suitable for rotary-wing UAV designs where arbitrary heading change and hovering are possible.

A. Scheduling Optimization

We first optimize the user scheduling $\mathbf{S}$ with given $\mathbf{Q}$ and $\mathbf{P}$. By using the epigraph form [32], (P) can be rewritten by

$$\text{(P1)}: \max_{r_S,\mathbf{S}} r_S \tag{13}$$

$$\text{s.t. } \frac{1}{N}\sum_{n\in\mathcal{N}} s_k[n]\zeta_k[n] \geq r_S, \forall k, \tag{14}$$

$$(1),\ (2), \tag{15}$$

where r_S is an auxiliary variable representing the minimum secrecy rate and we define

$$\zeta_k[n] \triangleq R_k[n] - \max_{j\neq k} R_j[n]. \tag{16}$$

Due to the binary variable $s_k[n]$, (P1) is still a non-convex problem. In [8], the user scheduling problem was solved by relaxing the binary constraint $s_k[n] \in \{0, 1\}$ to $0 \leq s_k[n] \leq 1$. However, such a relaxation approach would not guarantee the optimality for (P1) in general. Also, [28] and [29] focused only on a single ground user case, and thus the user scheduling issue in the UAV-aided secure network has not been studied. In the following proposition, we present a closed-form expression for the optimal solution of (P1).

Proposition 1: The optimal $s_k^\star[n]$ for (P1) is obtained by

$$s_k^\star[n] = \begin{cases} 1, & \text{for } \zeta_k[n] > 0, \\ 0, & \text{for } \zeta_k[n] \leq 0. \end{cases} \tag{17}$$

Proof. First, it is obvious that $s_k^\star[n] = 0$ if $\zeta_k[n] \leq 0$, since otherwise the objective value r_S would decrease. Also, one can see that although the solution $s_k^\star[n] = 1$ for $\zeta_k[n] > 0$ always increases the minimum secrecy rate r_S, it may not be feasible for (P1) due to the constraint $\sum_{k\in\mathcal{K}} s_k[n] \leq 1$. However, $s_k^\star[n] = 1$ for $\zeta_k[n] > 0$ is indeed a feasible solution because if $\zeta_k[n]$ is positive for some $k \in \mathcal{K}$, then we have $\zeta_j[n] \leq 0, \forall j \neq k$. Due to the definition of $\zeta_k[n]$ given in (16), there exists at most one $k \in \mathcal{K}$ such that $\zeta_k[n]$ is a positive number, implying that $\sum_{k\in\mathcal{K}} s_k^\star[n] \leq 1$. This completes the proof. ∎

From Proposition 1, the user scheduling solution $\mathbf{S}$ for given $\mathbf{Q}$ and $\mathbf{P}$ can be attained as a closed-form expression, which is different from [8] where the user scheduling problem is solved by convex optimization tools.

B. Power Optimization

Next, we determine the transmit power at the BS UAV and the jamming UAV for fixed user scheduling and trajectory. Let $\mathcal{N}_k \triangleq \{n|s_k[n] = 1\} \subset \mathcal{N}$ be the set of time slots at which user k is scheduled. Also, we denote $k_n \in \mathcal{K}$ as the scheduled user at time slot n. Then, by introducing the minimum secrecy rate variable r_P and new auxiliary variables $c_{k_n}[n]$, $\forall n$, (P) with given $\mathbf{S}$ and $\mathbf{P}$ is equivalently formulated as

$$\text{(P2)}: \max_{r_P,\mathbf{Q},\mathbf{C}} r_P \tag{18}$$

$$\text{s.t. } \frac{1}{N}\sum_{n\in\mathcal{N}_k} (R_k[n] - c_k[n]) \geq r_P, \forall k, \tag{19}$$

$$R_j[n] \leq c_{k_n}[n], \quad \forall j \neq k_n, n, \tag{20}$$

$$(6),\ (7), \tag{21}$$

where $\mathbf{C} \triangleq \{c_{k_n}[n], \forall n\}$. Due to the functions $R_{k_n}[n]$ in (19) and $R_j[n]$ in (20), (P2) is generally non-convex. Unlike [28] where the transmit power of the UAV can be obtained via simple line search method for a single legitimate user case, it is not straightforward to obtain the globally optimal solution for (P).

To tackle this issue, based on the analysis in [30], we successively approximate the original non-convex problem (P2) into a convex one at each iteration. Specifically, we find the surrogate functions of the non-convex constraints which satisfy the conditions in [30, Assumption 1]. First, for the scheduled user k_n, a concave lower bound $\tilde{R}_{k_n}^{(m)}[n]$ of $R_{k_n}[n]$ in (19) at the m-th iteration can be obtained by a Taylor expansion as [33]

$$\tilde{R}_{k_n}^{(m)}[n] \triangleq A_{k_n}[n] - \log\left(\sigma^2 + h_{J,k_n}[n]q_J^{(m-1)}[n]\right) - \frac{h_{J,k_n}[n]\left(q_J[n] - q_J^{(m-1)}[n]\right)}{\sigma^2 + h_{J,k_n}[n]q_J^{(m-1)}[n]}, \tag{22}$$

where $A_{k_n}[n]$ is defined as

$$A_{k_n}[n] \triangleq \log\left(\sigma^2 + \sum_{u\in\mathcal{U}} h_{u,k_n}[n]q_u[n]\right) \tag{23}$$

and $x^{(m)}$ stands for a quantity of x calculated at the m-th iteration.

To address the non-convexity of $R_j[n]$ in (20) for $j \neq k_n$, by employing a Taylor expansion, a convex upper bound $\tilde{R}_j^{(m)}[n]$ of $R_j[n]$ is given by

$$\tilde{R}_j^{(m)}[n] \triangleq \log\left(\sigma^2 + \sum_{u\in\mathcal{U}} h_{u,j}[n]q_u^{(m-1)}[n]\right) + \frac{\sum_{u\in\mathcal{U}} h_{u,j}[n]\left(q_u[n] - q_u^{(m-1)}[n]\right)}{\sigma^2 + \sum_{u\in\mathcal{U}} h_{u,j}[n]q_u^{(m-1)}[n]} + A_j[n], \tag{24}$$

where $A_j[n]$ for $j \neq k_n$ is defined as

$$A_j[n] \triangleq -\log\left(\sigma^2 + h_{J,j}[n]q_J[n]\right). \tag{25}$$

By applying (22) and (24), an approximated convex problem for (P2) at the m-th iteration can be expressed by

$$\text{(P2.1)}: \max_{r_P \geq 0, \mathbf{Q}, \mathbf{C}} r_P \tag{26}$$

$$\text{s.t. } \frac{1}{N}\sum_{n\in\mathcal{N}_k}\left(\tilde{R}_k^{(m)}[n] - c_k[n]\right) \geq r_P, \quad \forall k, \tag{27}$$

$$\tilde{R}_j^{(m)}[n] \leq c_{k_n}[n], \quad \forall j \neq k_n, n, \tag{28}$$

$$(6),\ (7). \tag{29}$$

Thanks to the convexity of (P2.1), it can be efficiently solved by utilizing convex optimization softwares, e.g., CVX [32].

C. Trajectory Optimization

In this subsection, the trajectory of the UAVs $\mathbf{P}$ is optimized for given $\mathbf{S}$ and $\mathbf{Q}$. First, we introduce new auxiliary variables $z_{u,k}[n], \forall u, k, n$, such that

$$z_{B,j}[n] \leq \|\mathbf{p}_B[n] - \mathbf{x}_j\|^2, \quad \forall j \neq k_n, n, \tag{30}$$

$$z_{J,k}[n] \leq \|\mathbf{p}_J[n] - \mathbf{x}_k\|^2, \quad \forall k, n. \tag{31}$$

Also, let us define $\hat{R}_k[n]$ as $\hat{R}_k[n] \triangleq A_k[n] + B_k[n]$ where

$$B_k[n] \triangleq \begin{cases} -\log\left(\sigma^2 + \frac{\rho_J q_J[n]}{H_J^2 + z_{J,k}[n]}\right), & \text{for } k = k_n, \\ \log\left(\sigma^2 + \sum_{u\in\mathcal{U}} \frac{\rho_u q_u[n]}{H_u^2 + z_{u,k}[n]}\right), & \text{for } k \neq k_n. \end{cases} \tag{32}$$

Then, the problem for finding the trajectory $\mathbf{P}$ can be reformulated as

$$\text{(P3)}: \max_{r_T, \mathbf{P}, \mathbf{V}, \mathbf{Z}} r_T \tag{33}$$

$$\text{s.t. } \frac{1}{N}\sum_{n\in\mathcal{N}_k}\left(\hat{R}_k[n] - v_k[n]\right) \geq r_T, \quad \forall k, \tag{34}$$

$$\hat{R}_j[n] \leq v_{k_n}[n], \quad \forall j \neq k_n, n, \tag{35}$$

$$(4),\ (5),\ (30),\ (31), \tag{36}$$

where the auxiliary variables r_T represents the minimum secrecy rate and we define $\mathbf{V} \triangleq \{v_{k_n}[n], \forall n\}$ and $\mathbf{Z} \triangleq \{z_{u,k}[n], \forall u, k, n\}$. The equivalence between (P3) and (P) for fixed $\mathbf{S}$ and $\mathbf{Q}$ can be verified, since at the optimal point of (P3), constraints (30) and (31) should hold with equalities. Otherwise, with the increased $z_{u,k}[n]$, we can increase $\hat{R}_{k_n}[n]$ and decrease $v_{k_n}[n]$ at the same time, which leads to the improved objective value r_T.

Still, (P3) is non-convex because of $A_k[n]$ in (23) and (25) and constraints (30) and (31). To this end, we utilize a similar approach in Section III-B. Observing that $A_{k_n}[n]$ in (23) is convex with respect to $\|\mathbf{p}_u[n] - \mathbf{x}_{k_n}\|^2$, its concave lower bound $\tilde{A}_{k_n}^{(m)}[n]$ at the m-th iteration can be computed as [8]

$$\tilde{A}_{k_n}^{(m)}[n] \triangleq \log\left(\sigma^2 + \sum_{u\in\mathcal{U}} h_{u,k_n}^{(m-1)} q_u[n]\right) - \sum_{u\in\mathcal{U}} C_{u,k_n}^{(m-1)}[n], \tag{37}$$

where

$$h_{u,k}^{(m)} \triangleq \frac{\rho_u}{H_u^2 + \|\mathbf{p}_u^{(m)}[n] - \mathbf{x}_{k_n}\|^2} \tag{38}$$

$$C_{u,k}^{(m)}[n] \triangleq \frac{\frac{h_{u,k}^{(m)}[n]q_u[n]}{H_u^2 + \|\mathbf{p}_u^{(m)}[n] - \mathbf{x}_k\|^2}}{\sigma^2 + \sum_{u\in\mathcal{U}} h_{u,k}^{(m)}[n]q_u[n]} \times \left(\|\mathbf{p}_u[n] - \mathbf{x}_{k_n}\|^2 - \|\mathbf{p}_u^{(m)}[n] - \mathbf{x}_{k_n}\|^2\right). \tag{39}$$

Similarly, a convex upper bound $\tilde{A}_j^{(m)}[n]$ of $A_j[n]$ in (25) for $j \neq k_n$ is given by

$$\tilde{A}_j^{(m)}[n] \triangleq C_{J,j}^{(m-1)} - \log\left(\sigma^2 + h_{J,j}^{(m-1)}[n]q_J[n]\right). \tag{40}$$

In addition, at the m-th iteration, the non-convex constraints in (30) and (31) can be approximated by applying a Taylor expansion to the right hand side as

$$z_{u,k}[n] \leq D_{u,k}^{(m)}[n] \leq \|\mathbf{p}_u[n] - \mathbf{x}_k\|^2, \tag{41}$$

Algorithm 1: Proposed algorithm for solving (P).

Initialize $m = 0$, $\mathbf{Q}^{(m)}$, and $\mathbf{P}^{(m)}$.
Repeat
Compute the solution $\mathbf{S}^{(m+1)}$ for (P1) from Proposition 1 with given $\mathbf{Q}^{(m)}$ and $\mathbf{P}^{(m)}$.
Compute the solution $\mathbf{Q}^{(m+1)}$ for (P2.1) with given $\mathbf{S}^{(m+1)}$, $\mathbf{Q}^{(m)}$, and $\mathbf{P}^{(m)}$.
Compute the solution $\mathbf{P}^{(m+1)}$ for (P3.1) with given $\mathbf{S}^{(m+1)}$, $\mathbf{Q}^{(m+1)}$, and $\mathbf{P}^{(m)}$.
Update $m \leftarrow m+1$.
Until convergence

where

$$D_{u,k}^{(m)}[n] \triangleq \|\mathbf{p}_u^{(m-1)}[n] - \mathbf{x}_k\|^2 + 2(\mathbf{p}_u^{(m-1)}[n] - \mathbf{x}_k)^T(\mathbf{p}_u[n] - \mathbf{p}_u^{(m-1)}[n]). \tag{42}$$

It is easy to check that $D_{u,k}^{(m)}$ is an affine function of $\mathbf{p}_u[n]$.

Combining these results, at the m-th iteration, we can construct a convex approximated problem for (P3) as

$$\text{(P3.1)}: \max_{r_T \geq 0, \mathbf{P}, \mathbf{V}, \mathbf{Z}} r_T \tag{43}$$

$$\text{s.t. } \frac{1}{N}\sum_{n\in\mathcal{N}_k}(\tilde{A}_k^{(m)}[n] + B_k[n] - v_k[n]) \geq r_P, \quad \forall k, \tag{44}$$

$$\tilde{A}_j^{(m)}[n] + B_j[n] \leq v_{k_n}[n], \quad \forall j \neq k_n, n, \tag{45}$$

$$z_{B,j}[n] \leq D_{B,j}^{(m)}[n], \quad \forall j \neq k_n, n, \tag{46}$$

$$z_{J,k}[n] \leq D_{J,k}^{(m)}[n], \quad \forall k, n, \tag{47}$$

$$(4),\ (5). \tag{48}$$

D. Joint Optimization Algorithm

Finally, we summarize a BSUM-based iterative algorithm in Algorithm 1 which successively solves (P1), (P2.1), and (P3.1) at each iteration. To prove the convergence of the proposed algorithm, let us define $R_{S,\min}(\mathbf{S},\mathbf{Q},\mathbf{P})$, $r_S(\mathbf{S},\mathbf{Q},\mathbf{P})$, $r_P(\mathbf{S},\mathbf{Q},\mathbf{P})$, and $r_T(\mathbf{S},\mathbf{Q},\mathbf{P})$ as the objective value of (P), (P1), (P2.1), and (P3.1) for given $\mathbf{S}$, $\mathbf{Q}$, and $\mathbf{P}$, respectively. Thus, it follows

$$R_{S,\min}\left(\mathbf{S}^{(m)},\mathbf{Q}^{(m)},\mathbf{P}^{(m)}\right) \tag{49}$$

$$\leq r_S\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m)},\mathbf{P}^{(m)}\right) \tag{50}$$

$$= R_{S,\min}\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m)},\mathbf{P}^{(m)}\right), \tag{51}$$

since $\mathbf{S}^{(m+1)}$ is the globally optimal solution for (P) with fixed $\mathbf{Q}^{(m)}$ and $\mathbf{P}^{(m)}$ as verified in Proposition 1.

Notice that (22) and (24) are tight bounds for the original problem (P) at a given local point $\mathbf{Q}^{(m)}$, i.e.,

$$R_{S,\min}\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m)},\mathbf{P}^{(m)}\right) = r_P\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m)},\mathbf{P}^{(m)}\right). \tag{52}$$

As the solution $\mathbf{Q}^{(m+1)}$ for (P2.1) is optimal for given $\mathbf{S}^{(m+1)}$, $\mathbf{Q}^{(m)}$, and $\mathbf{P}^{(m)}$, we have

$$r_P\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m)},\mathbf{P}^{(m)}\right) \tag{53}$$

$$\leq r_P\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m+1)},\mathbf{P}^{(m)}\right) \tag{54}$$

$$\leq R_{S,\min}\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m+1)},\mathbf{P}^{(m)}\right), \tag{55}$$

where the last inequality is obtained due to the fact that (P2.1) always provides a lower bound solution for (P). Similarly, it can be shown that

$$R_{S,\min}\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m+1)},\mathbf{P}^{(m)}\right) \tag{56}$$

$$\leq r_T\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m+1)},\mathbf{P}^{(m+1)}\right) \tag{57}$$

$$\leq R_{S,\min}\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m+1)},\mathbf{P}^{(m+1)}\right). \tag{58}$$

Combining (51)–(58) yields

$$R_{S,\min}\left(\mathbf{S}^{(m)},\mathbf{Q}^{(m)},\mathbf{P}^{(m)}\right) \tag{59}$$

$$\leq R_{S,\min}\left(\mathbf{S}^{(m+1)},\mathbf{Q}^{(m+1)},\mathbf{P}^{(m+1)}\right), \tag{60}$$

which indicates that the objective value of (P) is non-decreasing with respect to the iteration index m. Since the minimum secrecy rate $R_{S,\min}$ is upper-bounded by a finite value, the proposed algorithm is guaranteed to converge. Due to the convexity of the approximated problems (P2.1) and (P3.1), the proposed algorithm can be efficiently implemented in practice. Note that the proposed algorithm would require centralized computations at the UAVs with global information of the user locations.

IV. Numerical Results

In this section, we present numerical results for evaluating the performance of the proposed algorithm. We consider 10 MHz bandwidth at carrier frequency of 5 GHz [28]. The altitude and the maximum speed constraint of the UAVs are set to $H_u = 50$ m and $V_{\max,u} = 20$ m/s, $\forall u$, respectively, and the reference pathloss ρ_u at 1 m is assumed to be $\rho_u = -80$ dB, $\forall u$. Also, we employ $Q_{A,u} = 20$ dBm and $Q_{P,u} = 4Q_{A,u}$, $\forall u$, and the noise variance σ^2 is fixed to $\sigma^2 = -110$ dBm. For the simulations, we consider $K = 4$ ground users marked by black squares in Fig. 2 unless stated otherwise. The transmit power of the UAVs is initialized as $q_u^{(0)}[n] = Q_{A,u}$, $\forall u, n$, and we set the initial trajectory $\mathbf{P}^{(0)}$ of both UAVs to the solution of conventional minimum rate maximization scheme without secrecy consideration [8].

Fig. 2 exhibits the optimized trajectory computed from the proposed algorithm for $T = 30$ sec and 60 sec. In this plot, the circles stand for the location of the UAV sampled at every 5 sec. Also, the starting positions $\mathbf{p}_u[0]$ are marked by the filled circles. For comparison, we also depict the trajectory optimized by the conventional scheme in [8]. From the figure, we can see that regardless of the period T, the jamming UAV moves in the opposite direction to the BS UAV in order to efficiently jam the unscheduled users. For example, when the BS UAV supports user 1 (or user 4) by flying nearby areas, the jamming UAV is closely located to user 4 (or user 1). This is because

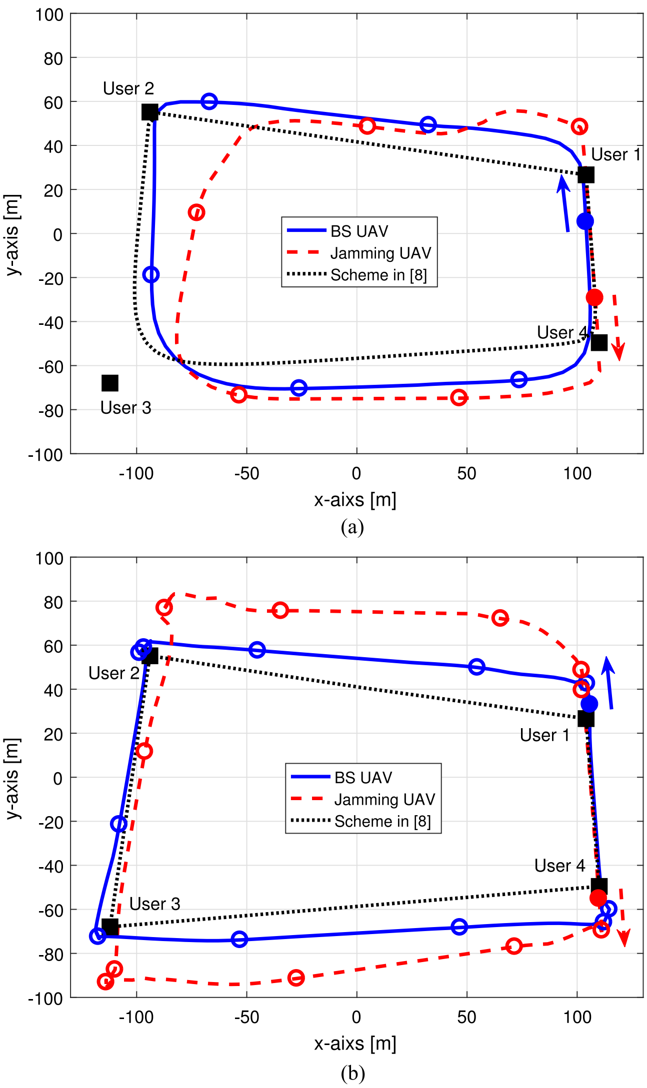

Fig. 2. Optimized trajectory for $T = 30$ sec and 60 sec.

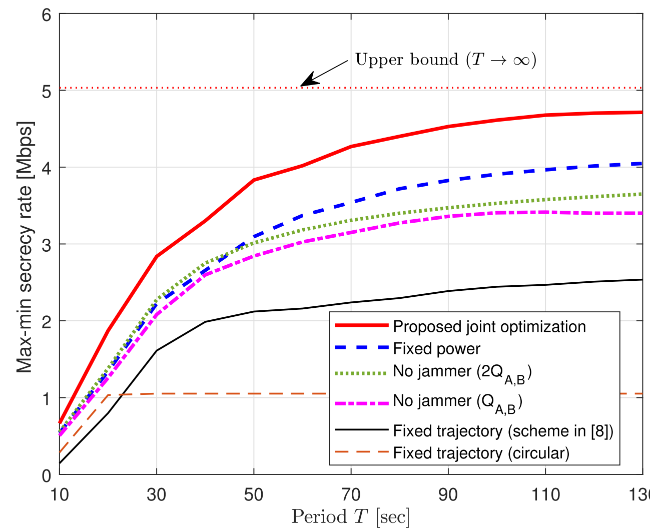

Fig. 3. Max-min secrecy rate performance as a function of T.

the secrecy rate of a user is dominated by the leaked rate of the nearest user. Therefore, to confidentially transmit the message intended to user 1 (or user 4), the jamming UAV focuses on its closest user, which is user 4 (or user 1). A similar phenomenon is observed for users 2 and 3. When the period is sufficiently large ($T = 60$), the trajectory of the scheme in [8], which does not consider the security issue, becomes a simple closed-loop path connecting all the user locations. In contrast, to enhance the secrecy rate performance, the UAVs in our system move in the vicinity of the users, but do not exactly reach at each user's position. This infers that the trajectory optimization in the secure UAV communications is significantly different from that in [8].

Fig. 3 illustrates the maximized minimum (max-min) secrecy rate performance of the proposed joint optimization algorithm as a function of the time period T. We compare the proposed algorithm with the following baseline schemes.[4]

- *Fixed power:* The proposed algorithm is adopted with fixed transmit power $q_u[n] = Q_{A,u}$, $\forall u, n$, and only the user scheduling and the trajectory are optimized by solving (P1) and (P3.1) iteratively.
- *No jammer:* The jamming UAV is not employed. Then, the transmit power and the trajectory of the BS UAV can be optimized by Algorithm 1 with $q_J[n] = 0, \forall n$.
- *Fixed trajectory:* The trajectory of the UAVs is fixed to that of the conventional minimum rate maximizing design [8] or a circular path centered at the geometrical mean of the users [8, Sec. III-E]. The user scheduling and the transmit power are optimized via the proposed algorithm.

For fair comparison, the performance of "No jammer" method is evaluated with the same power budget $Q_{A,B}$ at the BS UAV in the proposed algorithm and with twice power budget $2Q_{A,B}$ at the two UAVs. As a reference, we also plot an unachievable upper bound of the proposed algorithm with $T \to \infty$. First, it can be observed that as T gets larger, the max-min secrecy rate of all schemes monotonically increases. For all simulated periods, the proposed algorithm outperforms the baseline schemes. We can see that "Fixed power" performs better than "Fixed trajectory" methods, which indicates that for enhancing the secrecy rate performance, the trajectory optimization is more crucial than the transmit power control. Also, comparing the curves of the proposed algorithm and "No jammer", it can be verified that the cooperative jamming UAV significantly improves the max-min secrecy rate performance of the UAV-aided communications regardless of the power budget. At $T = 70$ sec, the proposed algorithm provides about 21%, 35%, and 93% performance gains over "Fixed power", "No jammer", and "Fixed trajectory", respectively.

In Fig. 4, we present the optimized trajectory of various baseline schemes for $T = 60$ sec, which corresponds to Fig. 2(b). It is interesting to see that the trajectory of the jamming UAV in "Fixed power" method is totally different from that of the proposed algorithm since the power control is not processed at both UAVs. As a result, the jamming UAV tries to adjust the received jamming interference power at the ground users by flying far away from them. Also, we can observe that the optimized trajectory of the BS UAV in "No jammer" scheme exhibits a lager closed-loop path compared to that in "Fixed power" method, because in the absence of the jammer, the confidential messages

[4]For a static setup where the UAVs are located at a fixed position as $\mathbf{p}_u[n] = \mathbf{p}_u, \forall u, n$, we cannot achieve a positive max-min secrecy rate.

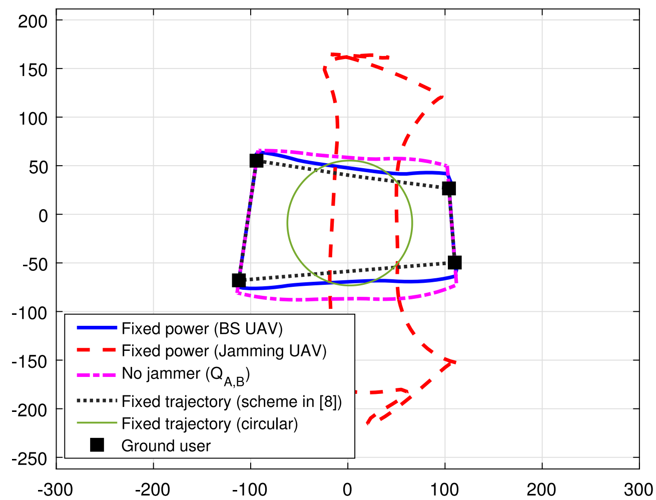

Fig. 4. Optimized trajectory of baseline schemes with $T = 60$ sec.

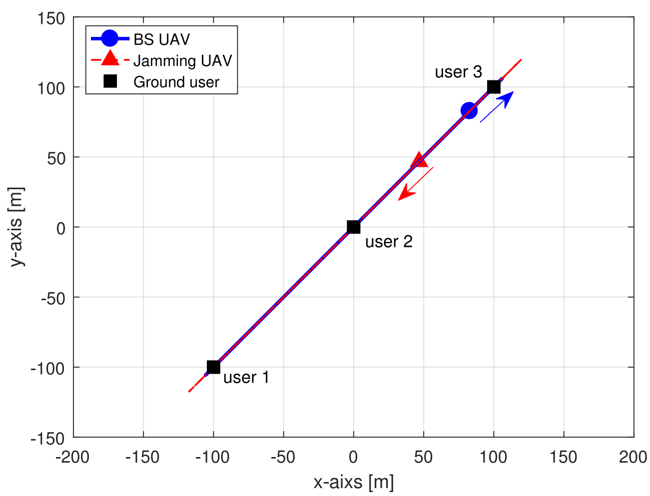

Fig. 5. Optimized trajectory for $T = 100$ sec when ground users are in a straight line.

would be more likely leaked to unscheduled users compared to the case with the jamming UAV.

Next, to obtain more insights behind the proposed optimization algorithm, we provide numerical results for several interesting ground user deployment scenarios. Fig. 5 depicts the optimized trajectory of the proposed algorithm for $T = 100$ sec in a case where $K = 3$ ground nodes are located in a straight line. Similar to Fig. 2, the jamming UAV moves in the opposite direction to the BS UAV. The max-min secrecy rate of the proposed algorithm is computed as 7.55 Mbps, which offers about a 40 % gain over "Fixed trajectory" method with the scheme in [8] that achieves 5.40 Mbps.

Fig. 6 plots the optimized trajectory of the proposed algorithm for $T = 50$ sec in a case where user 2 is far away from other users. In this example, the jamming UAV focuses on users 1 and 3 since the minimum secrecy rate is dominated by these closely located users, whereas the security of user 2 could be easily guaranteed only by the BS UAV. The max-min secrecy rate performance of the proposed algorithm and "Fixed trajectory" in [8] is given by 6.47 and 2.62 Mbps, respectively.

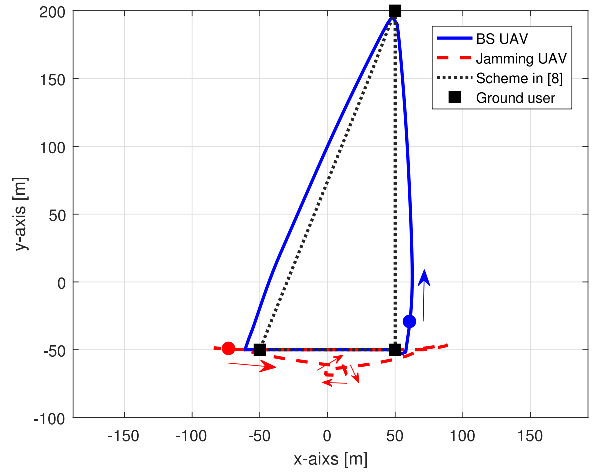

Fig. 6. Optimized trajectory for $T = 50$ sec when one ground user is far away from other users.

V. Conclusion

This paper has investigated the UAV-aided secure communications with a cooperative jamming UAV. The minimum secrecy rate has been maximized by jointly optimizing the transmit power, the trajectory of the UAVs and the user scheduling variables. Based on the BSUM framework, we have proposed an iterative algorithm which provides an efficient solution for the minimum secrecy rate maximization problem. Numerical results have verified that the proposed algorithm outperforms the baseline schemes. To combat with a scenario where the direct link between the BS UAV and the scheduled user is weak, studying relay UAV-assisted secure networks would be an interesting future research direction. Also, investigating delay-constrained applications [18] and an extension to general multi-UAV networks are worth pursuing.

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