

Joint 3D Trajectory and Tilt Angle Optimization for UAV-Assisted Secure Communications

Xingyu Du¹, Ping Yang¹, Yueling Zhao¹, Yue Xiao¹, Gang Wu¹, Sa Xiao¹, Vladimir Poulkov² and Zilong Liu³

¹ National Key Laboratory of Wireless Communications,

University of Electronic Science and Technology of China, Chengdu, 611731, China

² Faculty of Telecommunications, Technical University of Sofia, Sofia, Bulgaria

³ School of Computer Science and Electronics Engineering, University of Essex, Colchester, United Kingdom

Email: yang.ping@uestc.edu.cn

Abstract—To exploit the full spatial degrees of freedom (DoFs) and maximize the average secrecy rate in unmanned aerial vehicle (UAV)-assisted communication systems, this paper proposes a novel physical layer security (PLS) architecture that integrates the UAV's 3D kinematic trajectory with its tilt angle control. This joint design is particularly effective in the challenging scenario where the UAV, the legitimate receiver, and the eavesdropper are geometrically aligned. Furthermore, we develop an efficient alternating optimization (AO) framework to decouple the highly non-convex secrecy rate maximization problem, in which the tilt angle and the flight trajectory are iteratively optimized via a two-stage coarse-to-fine strategy and the successive convex approximation (SCA) method, respectively. Extensive simulation results demonstrate that by incorporating UAV tilt angle control, the proposed architecture liberates the UAV from taking power-consuming spatial detours, yielding a substantial 11.7% enhancement in the average secrecy rate compared to conventional trajectory-only baseline schemes.

Index Terms—Alternating optimization, antenna position and rotation optimization, physical layer security, trajectory design, unmanned aerial vehicle.

I. INTRODUCTION

THE advancement of sixth-generation (6G) networks and the low-altitude economy necessitates the integration of unmanned aerial vehicles (UAVs) into wireless communication systems [1], [2]. Compared to those in terrestrial networks, which often operate in richly scattering environments [3], line-of-sight (LoS) links can be easily provided by UAVs by leveraging their agility advantages [4], [5]. Such favorable propagation characteristics facilitate the deployment of UAVs as airborne mobile base stations to enhance coverage and data rates [6], [7]. On the other hand, these LoS-dominant links also introduce security vulnerabilities. Such links expose confidential signals to ground eavesdroppers through high-quality wiretap channels. To address this problem, physical layer security (PLS) for UAV-assisted systems attracts tremendous research attention in recent years [8].

A fundamental principle of PLS is to establish a channel capacity advantage for legitimate receivers over eavesdroppers. By optimizing flight trajectories, UAVs leverage their mobility to dynamically manipulate spatial channel conditions, creating

a channel gain disparity to hinder eavesdropping. Building upon this principle, various optimization frameworks have been developed to enhance security through trajectory design. For instance, the authors in [11] utilized successive convex approximation (SCA) to optimize the UAV trajectory by distancing the aircraft from ground eavesdroppers. Cooperative joint trajectory optimization schemes were developed in [12] and [13], utilizing jamming UAVs to emit artificial noise and actively degrade the eavesdroppers' signal-to-noise ratio. The average secrecy rate was maximized by jointly optimizing the swarm trajectory and virtual antenna array beamforming weights [14]. Furthermore, the authors in [15] explored deep reinforcement learning (DRL) for trajectory design to maximize the secrecy rate in complex scenarios. Collectively, these trajectory-based designs primarily exploit the UAV's spatial degrees of freedom (DoFs) to evade eavesdroppers by optimizing the flight path.

Despite their effectiveness, these trajectory-based designs suffer a limitation when the UAV, the legitimate receiver, and the eavesdropper become geometrically aligned. Under such conditions, the communication channels become highly correlated, making the spatial signatures nearly indistinguishable and thus forcing conventional schemes to rely on power-consuming spatial detours. However, such passive evasion degrades flight efficiency and limits the attainable secrecy rate, while deploying additional jammer UAVs incurs prohibitive hardware costs. Therefore, it is essential to conceive a cost-effective mechanism that harnesses additional DoFs to actively reshape the spatial channel manifold beyond physical mobility.

To this end, mechanical antenna rotation has been introduced in terrestrial base stations to provide such additional DoFs [16]–[18]. By adjusting the array orientation, these systems can actively reshape the spatial channel manifold. This allows for improved control over signal path correlation and helps separate overlapping spatial signatures without requiring extra physical movement. Inspired by this, we propose to leverage the UAV's tilt angles to control the rotation of its onboard uniform planar array (UPA), thereby incorporating the additional DoFs from antenna rotation into the UAV-PLS design. A UAV-PLS architecture that leverages the three-

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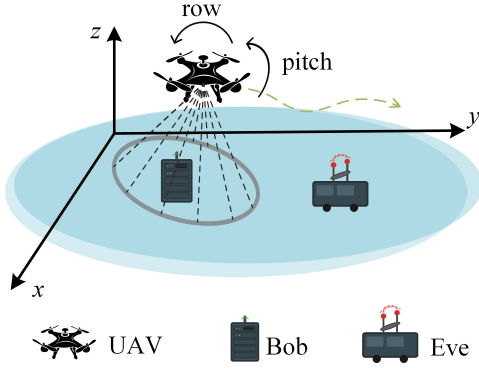


Fig. 1. System model of the UAV-assisted secure communication architecture.

dimensional (3D) attitude of the UAV to integrate trajectory design with UPA rotation control is introduced. We establish a system model that accounts for the 3D orientation of the aircraft and develop an alternating optimization (AO) framework to maximize the secrecy rate. Specifically, a coarse-to-fine strategy is used for rotation control, while the flight trajectory is optimized via SCA. Our design provides a practical way to enhance security by unlocking spatial dimensions that are usually limited by fixed-antenna setups.

II. SYSTEM MODEL

Motivated by the recent advances in aerial platforms, we conceive a novel UAV-assisted secure communication architecture. As shown in Fig. 1, a single UAV relies on a UPA for transmitting confidential information to a legitimate ground receiver (Bob) r , in the face of a malicious ground eavesdropper (Eve) e . As a benefit of its high degree of design-freedom, the UAV is capable of adaptively adjusting its tilt angles for the sake of dynamically altering the UPA's orientation. We will demonstrate that by jointly optimizing the mechanical tilt angles and the UAV's kinematic trajectory, our proposed system strikes a tradeoff between the achievable spatial degrees of freedom and the physical layer security attained in a low-altitude scenario.

A. UAV Kinematic Model

To facilitate the trajectory design, the total flight time is discretized into N equal time slots, indexed by $n \in \mathcal{N} \triangleq \{1, 2, \dots, N\}$, with each slot having a duration of T_{slot} . The UAV departs from an initial location $\mathbf{q}_s$ and reaches its final destination $\mathbf{q}_f$. To circumvent unrealistic instantaneous displacements, the maximum spatial deviation of the UAV within a single time slot is strictly constrained by $S_{\text{max}} = V_{\text{max}} T_{\text{slot}}$, where V_{max} is the maximum flying speed. The kinematic boundary constraints are compactly formulated as

$$\mathbf{q}[1] = \mathbf{q}_s, \quad \mathbf{q}[N] = \mathbf{q}_f, \quad (1)$$

$$\|\mathbf{q}[n] - \mathbf{q}[n-1]\| \leq S_{\text{max}}, \quad n = 2, \dots, N. \quad (2)$$

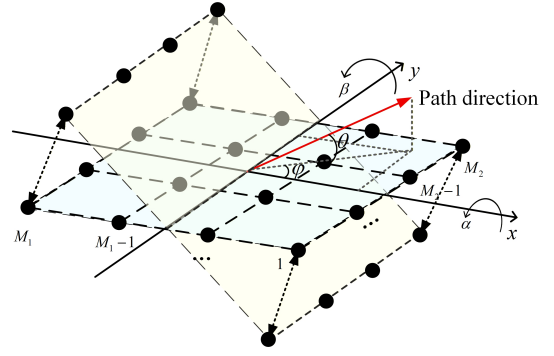


Fig. 2. 3D rotation model of the UAV-mounted UPA.

Furthermore, the UAV's mobility is bounded by a predefined 3D feasible region, defined by $W_{\min} \leq x[n] \leq W_{\max}$, $D_{\min} \leq y[n] \leq D_{\max}$, and $H_{\min} \leq z[n] \leq H_{\max}$, $\forall n \in \mathcal{N}$.

B. Rotation Model

As shown in Fig. 2, the UAV's spatial position $\mathbf{q}[n]$ inherently serves as the geometric center of the UPA. We assume that the UPA is rigidly mounted on the UAV, such that their physical rotations remain perfectly synchronized. In its default unrotated state, the UPA is deployed horizontally with an adjacent antenna element spacing of $d_0 = \lambda/2$. For the $M = M_1 M_2$ elements array, the absolute spatial coordinates of the (m_1, m_2) -th element prior to rotation, $\mathbf{q}_{m_1, m_2}[n] = [x_{m_1}[n], y_{m_2}[n], z_{m_1, m_2}[n]]^T$, naturally satisfy $x_{m_1}[n] - x_{m_1-1}[n] = d_0$, $y_{m_2}[n] - y_{m_2-1}[n] = d_0$, and $z_{m_1, m_2}[n] = z[n]$.

To dynamically reshape the spatial channel manifold, the UAV adjusts its mechanical tilt angles, characterized by the attitude vector $\mathbf{u}[n] = [\alpha[n], \beta[n]]^T$, where the roll $\alpha[n]$ and pitch $\beta[n]$ angles are bounded by their physical deflection limits:

$$|\alpha[n]| \leq \alpha^{\max}, \quad |\beta[n]| \leq \beta^{\max}, \quad \forall n \in \mathcal{N}. \quad (3)$$

where $|\cdot|$ denotes the absolute value of a scalar quantity.

By exploiting 3D rigid body kinematics, the composite rotation matrix $\mathbf{R}_u[n] = \mathbf{R}_\alpha[n]\mathbf{R}_\beta[n]$ is conceived, where the elemental rotation matrices are explicitly formulated as

$$\mathbf{R}_\alpha[n] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha[n] & -\sin \alpha[n] \\ 0 & \sin \alpha[n] & \cos \alpha[n] \end{bmatrix} \quad (4)$$

and

$$\mathbf{R}_\beta[n] = \begin{bmatrix} \cos \beta[n] & 0 & \sin \beta[n] \\ 0 & 1 & 0 \\ -\sin \beta[n] & 0 & \cos \beta[n] \end{bmatrix} \quad (5)$$

respectively.

Assuming perfect mechanical synchronization, the relative displacement vector spanning from the array center to the rotated (m_1, m_2) -th element is rigorously derived as

$$\mathbf{d}_{m_1, m_2}[n] = \mathbf{R}_u[n] (\mathbf{q}_{m_1, m_2}[n] - \mathbf{q}[n]). \quad (6)$$

C. Air-to-Ground Channel Model

Given the geographical location of the legitimate receiver r , denoted as $\mathbf{q}_r = [x_r, y_r, z_r]^T$, the instantaneous elevation angle of departure (AoD) $\theta_r[n]$ and the azimuth AoD $\varphi_r[n]$ are quantified by

$$\theta_r[n] = \arctan \frac{z[n] - z_r}{r_{xy}[n]}, \quad \varphi_r[n] = \arctan \frac{y[n] - y_r}{x[n] - x_r}, \quad (7)$$

where $r_{xy}[n] = \sqrt{(x[n] - x_r)^2 + (y[n] - y_r)^2}$. Exploiting the aforementioned AoDs, the unit directional vector pointing to the legitimate receiver is conceived as

$$\mathbf{f}_r[n] = [\cos \theta_r[n] \cos \varphi_r[n], \cos \theta_r[n] \sin \varphi_r[n], -\sin \theta_r[n]]^T. \quad (8)$$

Under the far-field propagation assumption, by amalgamating $\mathbf{d}_{m_1, m_2}[n]$ with $\mathbf{f}_r[n]$, the instantaneous steering vector of the UPA is formulated as

$$\mathbf{a}_r[n] = \left[e^{-j \frac{2\pi}{\lambda} \mathbf{f}_r[n]^T \mathbf{d}_{1,1}[n]}, \dots, e^{-j \frac{2\pi}{\lambda} \mathbf{f}_r[n]^T \mathbf{d}_{M_1, M_2}[n]} \right]^T. \quad (9)$$

To capture the large-scale fading behaviors, we employ a probabilistic LoS model with the composite channel power gain $G_r[n] = P_r^{\text{LoS}}[n] G_r^{\text{LoS}}[n] + P_r^{\text{NLoS}}[n] G_r^{\text{NLoS}}[n]$. The LoS probability is parameterized as $P_r^{\text{LoS}}[n] = (1 + a e^{-b(\theta_r[n] - a)})^{-1}$, with $P_r^{\text{NLoS}}[n] = 1 - P_r^{\text{LoS}}[n]$. The distance-dependent channel gains are defined as $G_r^{\text{LoS}}[n] = \beta_0 / \|\mathbf{q}[n] - \mathbf{q}_r\|^2$ and $G_r^{\text{NLoS}}[n] = \mu \beta_0 / \|\mathbf{q}[n] - \mathbf{q}_r\|^2$, where β_0 is the reference gain and $\mu \in (0, 1)$ denotes the Non-Line-of-Sight (NLoS) attenuation factor. Consequently, the baseband equivalent channel vector spanning to the legitimate receiver is encapsulated as $\mathbf{h}_r[n] = \sqrt{G_r[n]} \mathbf{a}_r[n]$. The eavesdropping channel vector $\mathbf{h}_e[n]$ towards Eve at $\mathbf{q}_e$ can be straightforwardly deduced analogously.

D. Problem formulation

Relying on the active beamforming weight vector $\mathbf{w}[n] \in \mathbb{C}^{M \times 1}$, the instantaneous achievable communication rates at node $k \in \{r, e\}$ are formulated as

$$R_k[n] = \log_2 \left(1 + \frac{|\mathbf{w}[n]^H \mathbf{h}_k[n]|^2}{\sigma^2} \right), \quad (10)$$

where σ^2 denotes the additive white gaussian noise (AWGN) variance. To maximize the beamforming gain under the power budget $P_{\max}$, the maximum ratio transmission (MRT) scheme is mathematically formulated as

$$\mathbf{w}[n] = \sqrt{P_{\max}} \frac{\mathbf{h}_r[n]}{\|\mathbf{h}_r[n]\|}, \quad \forall n \in \mathcal{N}. \quad (11)$$

Our ultimate objective is to maximize the average secrecy rate by striking an optimal synergy among the UAV rotation sequence $\mathbf{U} \triangleq \{\mathbf{u}[n]\}_{n=1}^N$ and the kinematic trajectory $\mathbf{Q} \triangleq \{\mathbf{q}[n]\}_{n=1}^N$. The comprehensive joint optimization problem is cast as

$$\begin{aligned} (\text{P1}) \quad & \max_{\mathbf{Q}, \mathbf{U}} \quad \bar{R}_{\text{sec}} = \frac{1}{N} \sum_{n=1}^N (R_r[n] - R_e[n]) \quad (12a) \\ & \text{s.t.} \quad (1), (2), (3), \text{ and} \\ & \quad W_{\min} \leq x[n] \leq W_{\max}, \quad \forall n, \\ & \quad D_{\min} \leq y[n] \leq D_{\max}, \quad \forall n, \\ & \quad H_{\min} \leq z[n] \leq H_{\max}, \quad \forall n. \quad (12b) \end{aligned}$$

III. JOINT OPTIMIZATION ALGORITHM

To tackle the intricately coupled variables formulated in the holistic optimization problem, we invoke the potent concept of alternating optimization (AO). Specifically, the original intractable problem is decoupled into two tractable subproblems: 1) the design of the UPA's mechanical rotation, and 2) the kinematic trajectory optimization. These subproblems are cyclically optimized in an iterative manner until convergence is attained.

A. Joint Optimization of Mechanical Rotation and Electronic Beamforming

For a given UAV location $\mathbf{q}[n]$, the spatial steering vectors are exclusively determined by the 3D attitude vector $\mathbf{u}[n]$. Under the adopted MRT scheme, the active beamforming vector is explicitly aligned with the legitimate channel. The instantaneous secrecy rate can be derived as a closed-form function of $\mathbf{u}[n]$, denoted as $\Xi[n]$. By substituting the MRT weight vector formulated in (11) into the rate expression (10) and exploiting the fundamental array property $\|\mathbf{h}_r[n]\|^2 = G_r[n]M$, the exact secrecy rate is formulated as:

$$\begin{aligned} \Xi[n] = & \log_2 \left(1 + \frac{P_{\max} G_r[n]^2 M}{\sigma^2} \right) \\ & - \log_2 \left(1 + \frac{P_{\max} G_r[n] G_e[n] f^2(\mathbf{u}[n])}{M \sigma^2} \right), \quad (13) \end{aligned}$$

where $f(\mathbf{u}[n]) = |\mathbf{a}_r[n](\mathbf{u}[n])^H \mathbf{a}_e[n](\mathbf{u}[n])|$.

It is intuitively observed from (13) that maximizing the secrecy rate is perfectly equivalent to minimizing the spatial correlation between the legitimate and the eavesdropping steering vectors. Hence, the objective function for the rotation optimization is elegantly distilled to

$$(\text{P2}) \quad \min_{\mathbf{u}[n]} \quad f(\mathbf{u}[n]) = |\mathbf{a}_r[n](\mathbf{u}[n])^H \mathbf{a}_e[n](\mathbf{u}[n])| \quad (14a)$$

$$\text{s.t.} \quad (3) \quad (14b)$$

Due to the periodic nature of the array manifold, the objective function $f(\mathbf{u}[n])$ is highly non-convex, exhibiting multiple local optima. Consequently, standard gradient-based methods are prohibitively sensitive to the initial conditions. To strike a compelling balance between the attainable performance and the imposed computational complexity, we conceive a two-stage *coarse-to-fine* optimization strategy. First, we discretize the feasible rotation domain into a uniform grid with a step size of Δ_u . An exhaustive search is performed over this

discrete set to identify a candidate point $\mathbf{u}[n]_{\text{grid}}^*$ that yields the minimum spatial correlation, thereby guaranteeing that the solution falls within the promising vicinity of the global optimum. Following this, by employing $\mathbf{u}[n]_{\text{grid}}^*$ as the initial point, we invoke the derivative-free Nelder-Mead simplex method to refine the solution, which flawlessly converges to a precise local minimum $\mathbf{u}[n]^*$ with high accuracy.

B. Kinematic Trajectory Optimization Design

Given the optimally configured mechanical antenna rotation $\mathbf{u}[n]$ and the electronic beamforming vector $\mathbf{w}[n]$, the instantaneous secrecy rate becomes fundamentally constrained by the large-scale spatial path loss, which is inextricably linked to the UAV's kinematic trajectory. By explicitly extracting the distance-dependent term, the achievable communication rates for the legitimate and eavesdropping channels can be elegantly rewritten as

$$R_k[n] = \log_2 \left(1 + \frac{L_k[n]}{\|\mathbf{q}[n] - \mathbf{q}_k\|^2} \right), \quad k \in \{r, e\}, \quad (15)$$

where the composite large-scale fading and beamforming gain parameters, $L_r[n]$ and $L_e[n]$, are respectively defined as

$$L_k[n] = \frac{\beta_0 (P_k^{\text{LoS}}[n] + \mu P_k^{\text{NLoS}}[n]) |\mathbf{w}[n]^H \mathbf{a}_k[n]|^2}{\sigma^2}, \quad k \in \{r, e\}. \quad (16)$$

Accordingly, the pure trajectory optimization subproblem, which aims to maximize the average secrecy rate subject to the flight kinematic constraints, is formulated as

$$(P3\text{-}a) \quad \max_{\mathbf{Q}} \quad \bar{R}_{\text{sec}} = \frac{1}{N} \sum_{n=1}^N (R_r[n] - R_e[n]) \quad (17a)$$

$$\text{s.t.} \quad (1), (2), (12b). \quad (17b)$$

Unfortunately, the objective function in (17) is inherently non-concave with respect to the trajectory variable $\mathbf{q}[n]$, rendering it exceptionally challenging to solve directly. To circumvent this severe non-convexity, we invoke the potent principles of successive convex approximation (SCA).

First, we introduce an auxiliary slack variable $S_r[n]$ to represent the upper bound of the squared distance spanning from the UAV to the legitimate receiver, yielding $\|\mathbf{q}[n] - \mathbf{q}_r\|^2 \leq S_r[n]$. Consequently, the legitimate rate exhibits the lower bound $R_r[n] \geq \log_2 (1 + L_r[n]/S_r[n])$. Since $1/S_r[n]$ is a strictly convex function with respect to $S_r[n]$, its first-order Taylor expansion at the given local point $S_r^{(k)}[n]$ extracted from the k -th iteration serves as a global linear lower bound. Thus, a mathematically tractable concave lower bound for $R_r[n]$ is derived as

$$R_r[n] \geq f_r[n] \triangleq \log_2 \left(1 + L_r[n] \left(\frac{2}{S_r^{(k)}[n]} - \frac{S_r[n]}{(S_r^{(k)}[n])^2} \right) \right). \quad (18)$$

Algorithm 1 Joint Optimization Algorithm

Require: Initial trajectory $\mathbf{Q}^{(0)}$, rotation angles $\mathbf{U}^{(0)}$, and iteration index $k = 0$;

1: **repeat**

2: $k \leftarrow k + 1$;

3: Update $\mathbf{U}^{(k)}$ by solving problem (14a) and calculate $L_r^{(k)}[n]$, $L_e^{(k)}[n]$ by (16) with given $\mathbf{Q}^{(k-1)}$;

4: Given $\mathbf{U}^{(k)}$, compute local Taylor expansion points;

5: Solve the convex problem (P3-b) using standard solvers to obtain $\mathbf{S}_r^{(k)}$, $\mathbf{S}_e^{(k)}$ and $\mathbf{Q}^{(k)}$;

6: **until** convergence criterion is met or the maximum number of iterations is reached;

Ensure: Optimized trajectory $\mathbf{Q}^*$, rotation angles $\mathbf{U}^*$;

Similarly, by introducing another slack variable $S_e[n]$ to actively bound the eavesdropping distance as $S_e[n] \leq \|\mathbf{q}[n] - \mathbf{q}_e\|^2$, we can handle this non-convex constraint by applying the first-order Taylor expansion at the local trajectory point $\mathbf{q}^{(k)}[n]$. This yields an affine and convex subset denoted as

$$S_e[n] \leq \left\| \mathbf{q}^{(k)}[n] - \mathbf{q}_e \right\|^2 + 2 \left(\mathbf{q}^{(k)}[n] - \mathbf{q}_e \right)^T \left(\mathbf{q}[n] - \mathbf{q}^{(k)}[n] \right). \quad (19)$$

C. Joint Optimization

By capitalizing on this affine approximation, a concave lower bound for the negative eavesdropping rate $-R_e[n]$ is masterfully constructed as

$$-R_e[n] \geq f_e[n] \triangleq -\log_2 \left(1 + \frac{L_e[n]}{S_e[n]} \right). \quad (20)$$

Finally, by substituting the original objective function with the established surrogate bounds $f_r[n]$ and $f_e[n]$, the initially intractable problem is elegantly reformulated into an approximate standard convex optimization problem denoted as

$$(P3\text{-}b) \quad \max_{\mathbf{Q}, \mathbf{S}_r, \mathbf{S}_e} \quad \tilde{R}_{\text{sec}} = \frac{1}{N} \sum_{n=1}^N (f_r[n] + f_e[n]) \quad (21a)$$

$$\text{s.t.} \quad (1), (2), (12b), (19) \quad (21b)$$

$$\|\mathbf{q}[n] - \mathbf{q}_r\|^2 \leq S_r[n], \quad \forall n, \quad (21c)$$

$$\|\mathbf{q}[n] - \mathbf{q}^{(k)}[n]\| \leq \Delta_{\text{tr}}, \quad \forall n, \quad (21d)$$

where $\mathbf{S}_r \triangleq \{S_r[n]\}_{n=1}^N$ and $\mathbf{S}_e \triangleq \{S_e[n]\}_{n=1}^N$ are the sets of auxiliary variables, and Δ_{tr} is the trust-region radius specifically imposed to rigorously ensure the approximation accuracy of the Taylor expansions. As (P3-b) strictly complies with the disciplined convex programming rules, it is readily amenable to computationally efficient off-the-shelf solvers, such as CVX.

The overall AO framework, systematically summarized in **Algorithm 1**, iteratively solves the decomposed subproblems until convergence is triggered after I_{AO} outer-loop iterations. Within each iterative stage, the total computational burden is dominated by the sequential execution of the rotation, and trajectory optimizations. Specifically, let B denote the grid

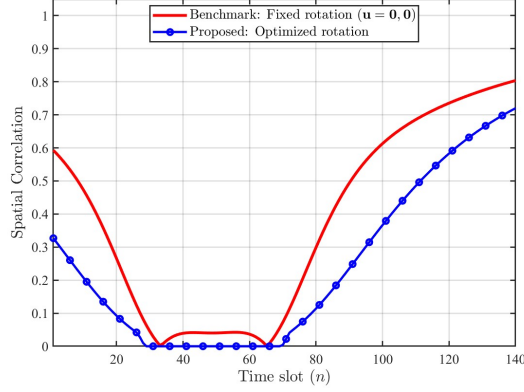


Fig. 3. The spatial correlation with dynamic rotation control.

set for angular search, I_u represent the number of iterations for Nelder-Mead simplex method. The mechanical rotation relying on a hybrid grid-search and Nelder-Mead method requires $\mathcal{O}(N(B + I_u)M)$ operations. Furthermore, solving the SCA-based trajectory subproblem via standard interior-point methods entails a worst-case complexity of $\mathcal{O}(N^{3.5})$. Consequently, the overarching computational complexity is rigorously bounded by

$$C_{\text{total}} = \mathcal{O}(I_{\text{AO}} [NM(B + I_u) + N^{3.5}]). \quad (22)$$

IV. PERFORMANCE EVALUATION

This section validates our proposed joint optimization algorithm in a $100 \times 100 \times [20, 40]$ m UAV scenario. Simulation parameters are: $T = 70$ s, $N = 140$ ($T_{\text{slot}} = 0.5$ s), $V_{\text{max}} = 2.5$ m/s, $P_{\text{max}} = 30$ dBm, and $\sigma^2 = -30$ dBm. The nodes are at $\mathbf{q}_r = [25, 50, 0]^T$ and $\mathbf{q}_e = [30, 35, 0]^T$. The channel models follow $\beta_0 = -30$ dB with LoS parameters $a = 10, b = 0.6$.

Fig. 3 illustrates the temporal evolution of the spatial correlation between the legitimate and eavesdropping channels. The conventional fixed-rotation baseline exhibits significantly higher correlation throughout the flight, implying that the UAV, Bob, and Eve frequently become geometrically aligned with nearly indistinguishable spatial signatures. By contrast, our proposed scheme dynamically adjusts the roll and pitch angles to effectively manipulate the array manifold. This agility unlocks crucial spatial degrees of freedom, gracefully circumventing the ubiquitous spatial correlation bottleneck.

Fig. 4(a) explicitly characterizes the instantaneous secrecy rate across the flight trajectory. The benchmark scheme relying exclusively on trajectory optimization (“TRA only”) suffers from a drastic performance penalty during the initial and final flight phases. During these segments, severe geometrical alignment critically erodes the attainable secrecy rate. Upon introducing dynamic rotation control, we witness a substantial enhancement. By actively reshaping the channel manifold via tilt angle adjustments, our scheme explicitly separates the beamforming directions in the spatial domain, even under

extremely challenging geometric alignments. Consequently, as quantitatively evidenced in Fig. 4(b), the joint antenna rotation optimization yields a substantial 11.7% average secrecy rate gain over the baseline.

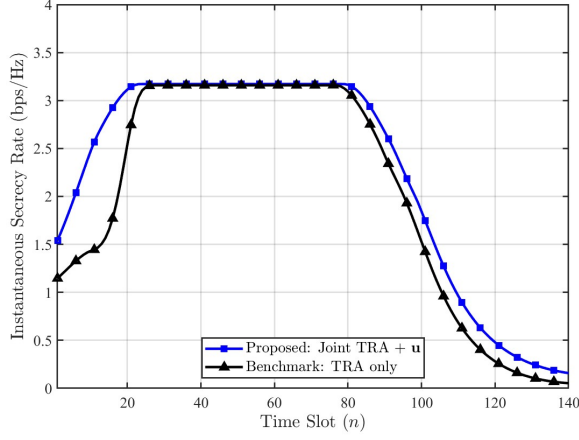
Fig. 5 depicts the optimized 3D flight trajectories and altitude variations. While all schemes fundamentally strive to approach Bob and evade Eve, the trajectory-only baseline is forced to take a significant spatial detour. Deprived of the spatial degrees of freedom provided by UAV rotation, it has no choice but to fly a longer distance to achieve physical separation. Conversely, upon introducing UAV rotation control, the trajectory shifts noticeably closer to Bob. By mechanically manipulating the array manifold to suppress information leakage in the spatial domain, the UAV is effectively liberated from the necessity of taking power-consuming long detours.

V. CONCLUSION

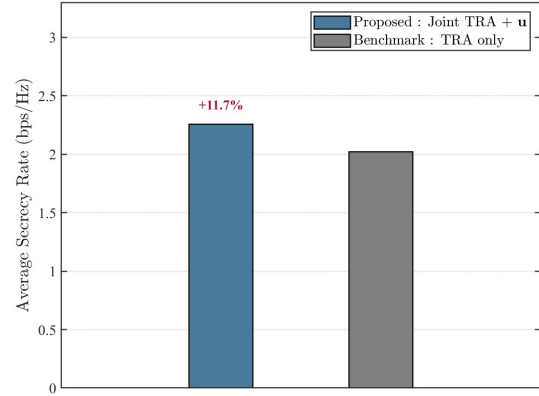
In this paper, we proposed a novel UAV-assisted secure communication architecture to tackle the ubiquitous spatial correlation bottleneck. By integrating the mechanical rotation of the UAV-mounted UPA with the 3D kinematic trajectory design, we successfully unlocked additional spatial DoFs. An efficient AO algorithm was developed to iteratively solve the highly non-convex joint design problem. Our extensive simulation results validated that dynamically adjusting the UAV’s tilt angles explicitly separates the spatial signatures of the legitimate user and the eavesdropper, even under challenging geometrical alignments. In a nutshell, this work provides a promising and power-efficient paradigm for securing low-altitude UAV communications.

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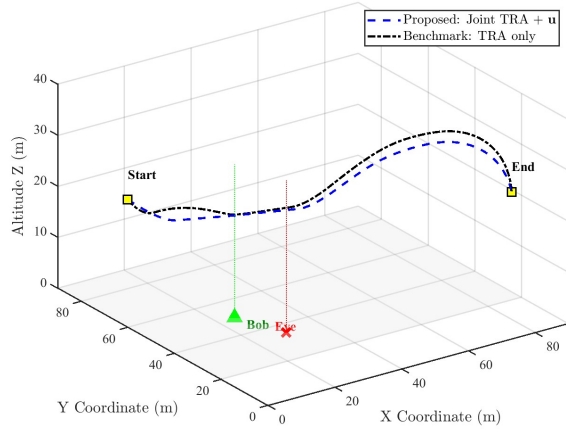


(a) Instantaneous secrecy rate

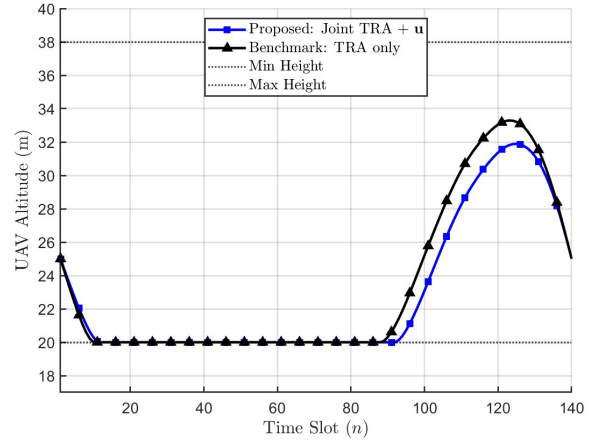


(b) Average secrecy rate

Fig. 4. Performance comparison of the achievable instantaneous and average secrecy rates under different optimization schemes.



(a) 3D flight trajectories



(b) Altitude variations

Fig. 5. Optimized 3D flight trajectories and altitude profiles, illustrating the elimination of spatial detours.

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