UAV-enabled optimal position selection for secure and precise wireless transmission

Tong Shen, Wenlong Cai, Yan Lin, Member, IEEE, Shuo Zhang, Jinyong Lin, Feng Shu, Member, IEEE 
and Jiangzhou Wang, Fellow, IEEE

Abstract—In this letter, two unmanned-aerial-vehicle (UAV) optimal position selection schemes are proposed. Based on the proposed schemes, the optimal UAV transmission positions for secure precise wireless transmission (SPWT) are given, where the maximum secrecy rate (SR) can be achieved without artificial noise (AN). In conventional SPWT schemes, the transmission location is not considered which impacts the SR a lot. The proposed schemes find the optimal transmission positions based on putting the eavesdropper at the null point. Thus, the received confidential message energy at the eavesdropper is zero, and the maximum SR achieves. Simulation results show that proposed schemes have improved the SR performance significantly.

Index Terms—Secure precise transmission, three-dimension, random-subcarrier-selection, direction modulation, machine learning

I. INTRODUCTION

As an ideal candidate way to achieve secure wireless transmission in physical layer [1–4], Directional modulation (DM) has attracted extensive scholars’ attention due to the characteristic that DM can transmit confidential signal to a specific direction [5–10]. In general, DM technology is implemented mainly by two methods. The first one is implemented on radio frequency (RF) frontend which utilize the phased array (PA) by optimizing the phase shifting [5–6]. The second method is implemented on the baseband by utilizing orthogonal vector [7] [8] or beamforming operations [9] [10]. As a further advance, to address the security problem in conventional DM system which cannot guarantee the secure transmission in distance dimension, a DM method based on frequency diverse array (FDA) [11–13] is proposed which achieves secure precise wireless transmission (SPWT) [14–17] in both direction and distance.

Nevertheless, the existing works on SPWT are based on the scenario with fixed transmitter, receiver and eavesdropper. In [17], it shows that the transmitter will form a mainlobe around the receiver and side-lobes outside the receiver, thus the position of transmitter also impact the transmission security a lot. Specifically, when the eavesdropper is located on the side-lobe peak, the secrecy performance will reduce a lot. Moreover, FDA-based SPWT scheme has increased the complexity significantly. Based on this background, this letter focus on the optimal transmission position without FDA. Our main contributions are summarized as follows:

1) Considering an unmanned-aerial-vehicle (UAV) transmission system with fixed receivers (desired user and undesired eavesdropper) and a predetermined height UAV transmitter, a 3D SPWT system with rectangular transmit antenna array is proposed. Without frequency diverse array (FDA), SPWT is achieved completely based on DM which reduced the complexity. Then, two transmission position optimization schemes in azimuth dimension and pitch dimension are proposed, respectively.

2) With the proposed schemes, artificial-noise (AN) is unnecessary in this system. All the transmit power is focus on transmitting confidential message while the received confidential signal power at the eavesdropper is zero. Thus, the memory for AN is unnecessary and the complexity can be reduced. Simulation results show that proposed schemes has the best secrecy rate (SR) than the conventional scheme without transmitting position selecting.

The remainder of this paper is organized as follows: In Section II, the proposed UAV SPWT system model is described. Then the UAV position selection schemes are proposed in Section III. Section IV presents the simulation and the analysis. Finally, the conclusion is drawn in Section V.

Notations: In this paper, scalar variables are denoted by italic symbols, vectors and matrices are denoted by bold letters of upper case, bold lower case, respectively. Sign $(\cdot)^T$, $(\cdot)^*$, $\text{tr}(\cdot)$ and $(\cdot)^H$ denote transpose, conjugation, trace and conjugate transpose respectively. $\|\cdot\|$ and $|\cdot|$ denote the norm and modulus respectively. $I_{M \times N}$ denotes the $M \times N$ identity matrix and $E[\cdot]$ denotes expectation operation.

II. SYSTEM MODEL

As shown in Fig. 1, the proposed SPWT system is composed of an UAV transmitter Alice, a desired user Bob and an eavesdropper Eve. Bob and Eve are equipped with a single antenna. The UAV is equipped with a $M \times N$ rectangular antenna array which has the same distance between two adjacent antenna elements.

Then, taking Bob as the origin, the ray formed from Bob to Eve is the positive direction of x-axis, a rectangular coordinate
system is established. In this paper, we assume that Bob and Eve are located on the ground, i.e., the Z axis coordinates of Bob and Eve are 0. Alice is flying at a predetermined height $g$ and parallel to the ground. Moreover, the position of Bob and Eve is known for Alice. Thus, the coordinate of Bob is defined as $(0,0,0)$, the coordinate of Eve is defined as $(X_E,0,0)$, and the coordinate of Alice is denoted as $(X_A,Y_A,g)$. $\theta_A \in (0,2\pi)$ is defined as the yaw angle of Alice which determines Alice’s flight direction, take the positive direction of X-axis as the reference direction and the counter clockwise direction as the positive direction.

Based on the established rectangular coordinate system, the angle relationship between Alice, Bob and Eve can be derived. The azimuth angles of Bob and Eve relative to Alice are derived as

$$\sin \theta_B = \frac{Y_A}{\sqrt{X_A^2 + Y_A^2}},$$
$$\cos \theta_B = \frac{X_A}{\sqrt{X_A^2 + Y_A^2}},$$

and

$$\sin \theta_E = \frac{Y_A}{\sqrt{(X_A-X_E)^2 + (Y_A)^2}},$$
$$\cos \theta_E = \frac{X_A-X_E}{\sqrt{(X_A-X_E)^2 + (Y_A)^2}}.$$  \hspace{1cm} (1)

The pitch angle of Bob and Eve relative to Alice are derived as

$$\cos \varphi_B = \frac{g}{\sqrt{(X_A)^2 + (Y_A)^2 + g^2}},$$
$$\cos \varphi_E = \frac{g}{\sqrt{(X_A-X_E)^2 + (Y_A)^2 + g^2}}.$$  \hspace{1cm} (2)

where $\varphi_B$ and $\varphi_E$ satisfy $0 \leq \varphi_B, \varphi_E \leq \frac{\pi}{2}$.

Since Alice is deployed with a $M \times N$ rectangular antenna array, we define the arrays parallel to the flight direction as rows, and arrays perpendicular to the direction of flight as columns. In the following, we use the subscript $m,n$ to denote the antenna in row $m$ and column $n$.

Then, the steering vector for the transmit antenna array is denoted by

$$h(\theta,\varphi) = \frac{1}{\sqrt{MN}} [e^{j2\pi \psi_{1,1}} \ldots e^{j2\pi \psi_{1,N}} \ldots e^{j2\pi \psi_{M,1}} \ldots e^{j2\pi \psi_{M,N}}],$$

where $\theta$ and $\varphi$ denote the receiver’s azimuth angle and pitch angle relative to Alice, respectively. $\psi_{m,n}$ is defined by

$$\psi_{m,n} = -\frac{f_c}{c}[(m-1)d \cos \theta \cos \varphi + (n-1)d \sin \theta \cos \varphi]$$

where $f_c$ is the central carrier frequency, $d = c/(2f_c)$ denotes the element spacing in the transmit antenna array, and $c$ is the light speed. Substituting $(\theta_B,\varphi_B)$ and $(\theta_E,\varphi_E)$ into (7) and (8), we can obtain the steering vector $h(\theta_B,\varphi_B)$ and $h(\theta_E,\varphi_E)$, respectively.

In conventional baseband DM system, the transmit signal can be expressed as

$$s = \sqrt{\alpha P_s v_x} + \sqrt{(1-\alpha)P_s} w,$$

where $\alpha$ denotes the power allocation factor, $P_s$ is the total transmit power, $v$ is a complex signal symbol with $\mathbb{E}[|v|^2] = 1$, $v$ denotes the beamforming vector and $w$ denotes the AN vector.

In general, we set $v = h(\theta_B,\varphi_B)$ to maximize the received confidential signal power at Bob, while $w$ is set as

$$w = [I - h(\theta_B,\varphi_B) h^H(\theta_B,\varphi_B)] z,$$

where $z \sim \mathcal{CN}(0,I_{M \times N})$.

In this letter, all the channels are set as the line of sight (LOS) ones and the channel are unobstructed between the transmitter and the receivers, which can be justified in UAV communications. Moreover, without loss of generation, the channel gain is set as 1 and phase compensation is employed at the receivers. Based on this background, the received signal at Bob can be expressed as

$$y_B = h^H_B s + n_B = \sqrt{\alpha P_s} h^H_B v x + \sqrt{(1-\alpha)P_s} h^H_B w + n_B$$
$$= \sqrt{\alpha P_s} v x + n_B,$$

and the received signal at Eve can be expressed as

$$y_E = h^H_E s + n_E = \sqrt{\alpha P_s} h^H_E v x + \sqrt{(1-\alpha)P_s} h^H_E w + n_E.$$  \hspace{1cm} (12)

In (11) and (12), $h_B$ and $h_E$ are the abbreviation of $h(\theta_B,\varphi_B)$ and $h(\theta_E,\varphi_E)$, respectively. $n_B$ and $n_E$ are the additive white Gaussian noise (AWGN) with distributed as $n_B \sim \mathcal{CN}(0,\sigma_B^2)$ and $n_E \sim \mathcal{CN}(0,\sigma_E^2)$, respectively.
III. PROPOSED UAV POSITION SELECTION SCHEME

In conventional DM system, the desired receiver has the maximum confidential signal power which is shown in (11). However, this scheme cannot guarantee a minimum confidential signal power at Eve which is related to $h_E$, i.e., the relative position of Eve, thus the security for confidential signal transmission cannot be guaranteed. To maximize the security rate (SR), we propose an optimal UAV position selection scheme to achieve the maximum SR.

According to the definition of SR, we have

$$\text{SR} = \log(1 + \text{SINR}_B) - \log(1 + \text{SINR}_E).$$  \hspace{1cm} (13)

As shown in (11), when $v = h_B$, SINR$_B$ has the maximum value $\frac{\alpha P_s |h_B^H h_B|^2}{(1 - \alpha) P_s |h_E^H w + \sigma^E}$. Thus, the optimization problem is constructed as

$$\min_{\theta_E, \varphi_E} \text{SINR}_E,$$  \hspace{1cm} (14)

where

$$\text{SINR}_E = \frac{\alpha P_s |h_B^H h_B|^2}{(1 - \alpha) P_s |h_E^H w + \sigma^E}.$$  \hspace{1cm} (15)

Note that,

$$h_E^H h_B = \frac{1}{MN} \sum_{m,n} e^{j\pi[(m-1)\cos\theta_E + (n-1)\sin\theta_E]} \cos\varphi_E,$$

$$e^{-j\pi[(m-1)\cos\theta_B + (n-1)\sin\theta_B]} \cos\varphi_B,$$  \hspace{1cm} (16)

when $h_E^H h_B = 0$, the SINR at Eve is zero, which means the maximum value of SR is reached. Then, we find the optimal UAV position where the relative position of Eve lies on the nulls of SINR. Since the azimuth angle and the pitch angle are coupled, we derive the null points along the azimuth angle dimension and the pitch angle dimension, respectively.

A. Azimuth angle dimension

According to (16), let $\varphi_B = \varphi_E$, the null points of array pattern along the azimuth angle dimension satisfy the following condition (18).

$$h_E^H h_B = \frac{1}{MN} \sum_{m,n} e^{j\pi[(m-1)(\cos\theta_E - \cos\theta_B)] \cos\varphi_E},$$

$$= \frac{1}{MN} \sum_{m,n} e^{jM\pi(\cos\theta_E - \cos\theta_B) \cos\varphi_E - 1}.$$  \hspace{1cm} (17)

Let $h_E^H h_B = 0$, we have,

$$M\pi(\cos\theta_E - \cos\theta_B) \cos\varphi_E = \pm 2k\pi,$$

$$k \neq k' M(k' = 1, 2, 3, \ldots).$$  \hspace{1cm} (18)

or

$$N\pi(\sin\theta_E - \sin\theta_B) \cos\varphi_E = \pm 2k\pi,$$

$$k \neq k' N(k' = 1, 2, 3, \ldots).$$  \hspace{1cm} (19)

Then, the relationship $\theta_E$ and $\theta_B$ can be obtained as,

$$\cos\theta_E - \cos\theta_B = \frac{\pm 2k}{M \cos\varphi_E},$$

$$k \neq k' M(k' = 1, 2, 3, \ldots).$$  \hspace{1cm} (20)

or

$$\sin\theta_E - \sin\theta_B = \frac{\pm 2k}{N \cos\varphi_E},$$

$$k \neq k' N(k' = 1, 2, 3, \ldots).$$  \hspace{1cm} (21)

Note that, the pitch angle satisfies the constraint of $\varphi_B = \varphi_E$. According to (5) and (6), the X-coordinate of Alice must have the maximum $\theta_E$ position where the relative position of Eve lies on the nulls of SINR. Therefore, the null points of $\cos\theta_E - \cos\theta_B$ and $\sin\theta_E - \sin\theta_B$ can be obtained as,

$$\cos(\theta_E - \theta_B) - \cos(\theta_B - \theta_A) = \frac{\pm 2k}{M \cos\varphi_E},$$

$$k \neq k' M(k' = 1, 2, 3, \ldots).$$  \hspace{1cm} (22)

or

$$\sin(\theta_E - \theta_A) - \sin(\theta_B - \theta_A) = \frac{\pm 2k}{N \cos\varphi_E},$$

$$k \neq k' N(k' = 1, 2, 3, \ldots).$$  \hspace{1cm} (23)

According to the sum-to-product formulations, (22) and (23) can be further transformed as

$$\cos\theta_B = \frac{\pm k}{M \cos\varphi_E \cos\theta_A},$$

$$k \neq k' M(k' = 1, 2, 3, \ldots).$$  \hspace{1cm} (24)

or

$$\cos\theta_B = \frac{\pm k}{M \cos\varphi_E \sin\theta_A},$$

$$k \neq k' N(k' = 1, 2, 3, \ldots).$$  \hspace{1cm} (25)

Note that $\cos\varphi_E$ is a monotone increasing function about $Y_E$ in the range of $(-\infty, 0)$, while monotone decreasing in the range of $(0, +\infty)$. Thus, $\frac{1}{N \cos\varphi_E}$ is valued from $\frac{1}{\sqrt{X_E^2/2}}$ to $\frac{1}{\sqrt{X_E^2/2 + g^2}}$ about $Y_E$ in the range of $(-\infty, 0)$, and is valued from $\frac{1}{N \cos\varphi_E}$ to $\frac{1}{N \cos\varphi_E}$ about $Y_E$ in the range of $(0, +\infty)$. Herein, $\cos\varphi_0$ is defined as

$$\cos\varphi_0 = \frac{X_E/2}{\sqrt{(X_E/2)^2 + g^2}}.$$  \hspace{1cm} (26)

Since $\theta_B$ is valued in $(-\pi/2, \pi/2)$, we have $\cos\theta_B \in (0, 1)$. Thus, with a proper value of $k$, (24) and (25) must have a solution. Then, the solution can be obtained easily by dichotomy method or linear search method.

Based on this background, the Y-coordinate of Alice can be obtained. With the obtained position of Alice, the SINR at Eve is zero while the SINR at Bob achieves the maximum value. Thus, we get the maximum value of SR, the transmission security is guaranteed.
B. Pitch angle dimension

Let $\theta_B = \theta_E$, the null points of array pattern along the pitch angle dimension satisfy the following condition

$$h_E^H h_B = \frac{1}{MN} \sum_{m}^{M} e^{j \pi (m-1)} \cos \theta E \left( \cos \varphi E - \cos \varphi_B \right),$$

$$= \frac{1}{MN} \left[ e^{j \pi \cos \theta E \left( \cos \varphi E - \cos \varphi_B \right)} - 1 \right].$$

Similarly, let $h_E^H h_B = 0$, we have,

$$M \pi \cos \theta E \left( \cos \varphi E - \cos \varphi_B \right) = \pm 2l\pi,$$

or

$$N \pi \sin \theta E \left( \cos \varphi E - \cos \varphi_B \right) = \pm 2l\pi,$$

Then, the relationship $\varphi E$ and $\varphi_B$ can be obtained as,

$$\cos \varphi E - \cos \varphi_B = \frac{\pm 2l}{M \cos \theta E},$$

$$l \neq \frac{1}{M} \left( l' = 1, 2, 3, \ldots \right).$$

or

$$\cos \varphi E - \cos \varphi_B = \frac{\pm 2l}{N \sin \theta E},$$

$$l \neq \frac{1}{N} \left( l' = 1, 2, 3, \ldots \right).$$

Note that, the azimuth angles satisfy the constraint of $\theta_B = \theta_E$. According to $\left[ O \right] \sim \left[ I \right]$, the Y-coordinate of Alice must satisfy $Y_A = 0$. Since the azimuth angle can be adjusted with the flight angle of Alice, i.e. the flight direction which we defined as $\theta_A$, its value range is $(0, 2\pi)$. The X-coordinate range of Alice is $(-\infty, 0) \cup (X_E, +\infty)$ while $\cos \varphi E - \cos \varphi_B$ is a monotone decreasing function about $X_A$. Let $l = 1$, it is clear that when $\frac{2}{M \cos \theta_E} < 0$ or $\frac{2}{N \sin \theta E} < 0$, the X-coordinate $X_A \in (-\infty, 0)$. Conversely, when $\frac{2}{M \cos \theta E} > 0$ or $\frac{2}{N \sin \theta E} > 0$, the X-coordinate $X_A \in (X_E, +\infty)$. Thus the value of $X_A$ can be easily obtained by dichotomy method.

C. Performance analysis

With the obtained position of Alice in Section III-A or III-B, the value of $h_E^H h_B$ is zero, which means the SINR at Eve is zero, i.e., $SINR_E = 0$. While at the same time, the SINR at Bob achieves the maximum value, i.e., $SINR_B = \frac{\alpha P_S}{\sigma_B^2}$. Thus, we get the maximum value of SR which is given by

$$SR = \log \left( 1 + \frac{\alpha P_S}{\sigma_B^2} \right).$$

Thus, the transmission security can be guaranteed. Moreover, we can observe in $\left[ 32 \right]$, the power allocation factor should be as large as possible. When $\alpha = 1$, the SR achieves the maximum value $\log \left( 1 + \frac{P_S}{\sigma_B^2} \right)$. Thus, the AN in our proposed scheme is unnecessary, which means all the transmit power is used to transmit the confidential signal. Another benefit is that the memory for AN can be omitted and reduce the budget, the memory efficiency will be significantly improved.

IV. SIMULATION RESULTS AND ANALYSIS

In this section, we evaluate the performance of our proposed schemes by numerical simulations. The default system parameters are chosen as shown in Table I. By default, we assume $\sigma_B^2 = \sigma_E^2$, $k$ and $l$ in $\left[ 24 \right], \left[ 25 \right], \left[ 20 \right]$, and $\left[ 21 \right]$ are both set as 1.

Fig. 2 illustrates the curves of the SR versus SNR for proposed azimuth-dimension scheme and three random position with conventional scheme. Fig. 3 illustrates the curves of the SR versus SNR for proposed pitch-dimension scheme and three random position with conventional scheme. It is clear to see that, when Alice is located at the position obtained by the proposed schemes, the SR performance are better than the positions obtained by conventional scheme. Moreover, with the increase of SNR, the SR gaps between the proposed schemes and conventional scheme are increasing. Furthermore, the curves of derived theoretical SR of proposed schemes versus SNR are shown in Fig. 2 and Fig. 3. Compared the theoretical SR curve to the simulated one, the gap almost disappear as the SNR increases. This verifies the validness of our expression in $\left[ 32 \right]$. 

### TABLE I

| Parameter                          | Value         |
|-----------------------------------|---------------|
| The number of transmitter antennas $(M \times N)$ | $4 \times 4$  |
| Total signal bandwidth (B)        | 5MHz          |
| Total transmit power $(P_t)$       | 1W            |
| The height of Alice $(q)$         | 200m          |
| The eavesdropper’s position $(X_E, Y_E)$ | (500m,0)     |
| The flight angle of Alice $(\theta_A)$ | $\pi/4$       |
| Central carrier frequency $(f_c)$  | 3GHz          |
Fig. 3. Curves of SR versus SNR for proposed pitch dimension scheme and conventional scheme. This verifies that, the UAV at the position with the proposed schemes have the superior secrecy rate performance and simulations, our proposed methods have much better SR performance than conventional methods.

V. Conclusion

In this letter, we proposed two UAV optimal transmission position selection methods. Compared to the conventional methods, the proposed schemes have the superior secrecy rate performance. Besides, the proposed schemes do not need the aided AN, all the transmission power is used to transmit confidential message, this increases the energy efficiency while reduces the complexity and save the budget. From the analysis and simulations, our proposed methods have much better SR performance than conventional methods.

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