Time-varying Array and Polarization Filtering Based Transmission Scheme for Secure Dual-polarized Wireless Communications

Zhangkai Luo, Zhongmin Pei*, Xinmin Wang

Science and Technology on Complex Electronic System Simulation Laboratory, Space Engineering University, Beijing, China

luo_zhangkai@126.com, peizhongmin@tsinghua.org.cn, 13391709986@163.com

Keywords: wireless communication; information security; polarization filtering

Abstract: In this paper, a transmission method base on time-varying array and polarization filtering is proposed to enhance the information security in wireless communications. Indeed, the information is firstly divided into two parts and respectively modulated into amplitude-phase symbols. Then, two sets of symbols respectively multiply with two polarization states (PS), which are orthogonal to each other. After that, the two signals are added up to be mixed signals for transmission by the dual-polarized phased array. To enhance the information security, transmit antennas of the dual-polarized phased array are randomly chosen, thus the amplitude and phase of all directions vary randomly except for the main lobe, which leads to the distortion of the constellation structure at the eavesdropper side. In this way, the PSs of two signals are difficult to crack and the transmission security is ensured. Finally, simulations demonstrate the proposed can effectively deteriorate the bit error performance of eavesdroppers by distorting the constellation in sidelobes.

1. Introduction

Along with the development of wireless communication technology, the number of users accessing the network is growing rapidly, which causes the spectrum resource more and more limited. To face the problem, the frequency of communication is getting higher and higher [1, 2]. In this condition, the channel information state (CSI) is different from that in low frequency where the line-of-sight (LOS) component occupies a larger proportion, which leads to the correlation of the spatial components at the receiver side even the transmitting antennas are separated at half wavelength. In addition, the refraction and scattering components are negligible, and receivers can only discover one transmission path since most receivers' sensitivity are not enough to distinguish the different spatial signatures[3]. Therefore, even multiple antennas are used, it is still unable to create multipath to improve the throughput. Hence, multi-input multi-output (MIMO) gains are hardly available in high frequency case for its gains depend on the decorrelation between channels.

Fortunately, in recent years, dual-polarized antenna technologies have been developed rapidly, and the applications in wireless communication are more extensive[4]. Base on dual-polarized antennas, two independent channel can be provided in the LOS scenario with the same carrier frequency, which is mainly because of the orthogonal polarization could be separated by the non-zero cross-polarization discrimination (XPD). In addition, a lot of polarization signal processing techniques can be applied to improve the transmission efficiency, such as polarization diversity and polarization multiplexing [5], polarization state modulation (PM)[6], polarization filtering (PF)[7] and so on. As in [6], the amplitude ratio and phase difference of orthogonal polarization signal, which are called the polarization state (PS), are utilized as the information bearing parameters. This is mainly because the PS can be represented by a unique point on the Poincare. For PM, the PS is used to convey information, which realizes a kind of three-dimensional modulation technique [8]. In addition, it could be combined with traditional amplitude-phase modulation technology, thus, it improved the transmission efficiency. For PF in [9], the PS was utilized as the attribute of the signal for multiple-signal separation, thus, the information could be carried by multiple polarization signals and transmitted in parallel[7], in this way , the transmission efficiency was improved.

Despite of the above advantages, information security is a fundamental problem in wireless communication due to the openness nature of the wireless medium. If the signal are transmitted without any safeguard procedures, the same information could be recovered at the eavesdroppers side, even in the sidelobes[10]. Therefore, to enhance the transmission security, one should prevent eavesdroppers from decoding any useful message intended to the desired user. When locations of eavesdroppers are known beforehand, nulls could be formed in the eavesdropper directions with beamforming techniques [11] to prevent eavesdropping. However, such information is hard to obtain in practical, especially for passive ones.

To solve the problem, the idea of directional modulation is considered in this paper that the constellation structure of the signal is kept unchanged in the desired direction while naturally distorted in undesired directions[12]. In the proposed method, the information is divided into two parts and respectively modulated into symbols. Then, two sets of symbols respectively multiply with two polarization states (PS) , which are orthogonal to each other. After that, the two signals are added up for transmission through two orthogonal polarized beams, which are formed by the dual-polarized phased array. In addition, the antennas used to form the beams are changing unregularly, which makes the constellation structures varies in undesired directions. Thus, the information security is ensured. For legal users, the received signals are separated into two parts by the polarization filtering matrix constructed with the shared PS between the transmitter and the legal users. Then, two parts of signals are further demodulated without mutual interferences. While for eavesdroppers, the amplitude and phase of received signals are distorted, which is difficult to crack. In this case, two signals can not be completely separated, which leads to the self-interferences in received signals. In this manner, the transmission security is enhanced. Finally, theoretical analysis and simulation results demonstrate the security performance of the proposed method.

2. System Model

Assuming a transmitter Alice equipped with N dual-polarized antennas, which are placed along the y-axis and centered at the origin and the broadside angle is along the positive x-axis as shown in Fig.1. A legal user Bob and an eavesdropper Eve. For Bob, a dual-polarized antenna is utilized for signals reception; For Eve, a dual-polarized antenna is equipped for signals reception. If the signals are broadcast from Alice without any protection, even Eve is located in sidelobes, the same information are possibly recovered. To prevent eavesdropping, we propose a time-varying array and polarization filtering based method to enhance the transmission security. In our research, the channel is assumed to be ideal, where the mutual interferences between orthogonal polarizations are not taken into consideration since this kind of interferences can be eliminated by the ZF method or the pre-compensation method [13].

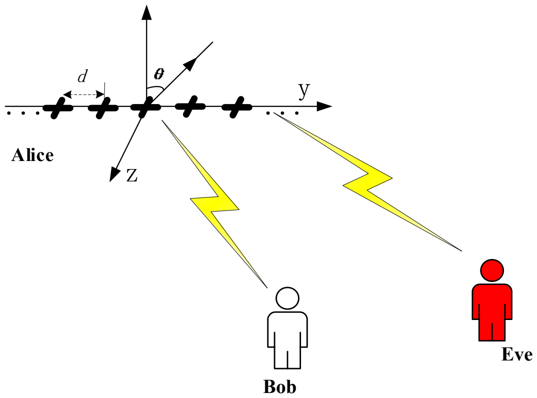


Figure 1 System model

3. Signal model and problem description

The k-th polarized signal can be written as [14]

$$x_k = \begin{bmatrix} s_{\mathrm{H}k} \\ s_{\mathrm{V}k} \end{bmatrix} = \begin{bmatrix} \cos\gamma_k \\ \sin\gamma_k e^{j\eta_k} \end{bmatrix} A_k e^{j\varphi_k} \quad (1)$$

where $\gamma_k \in \left[0, \frac{\pi}{2}\right]$ denotes the polarized angle; $\eta_k \in [0, 2\pi]$ denotes the phase difference; $A_k e^{j\varphi_k}$ denotes the k-th amplitude-phase modulation signal, where A denotes the amplitude and φ denote the phase. $\mathbf{P}_k = \begin{bmatrix} \cos\gamma_k \\ \sin\gamma_k e^{j\eta_k} \end{bmatrix}$ is the PS.

A N^2-element dual-polarized phased array is used to form two beams, which results into the horizontal (H) beam $f_{\mathrm{H}}(\theta,\varphi)$ and vertical (V) polarized beam $f_{\mathrm{V}}(\theta,\varphi)$, to transmit signals. Then, two components of $\mathbf{s}_k$ are transmitted by two polarized beams, respectively. Thus, the k-th received signal can be represented as

$$\mathbf{y}_k = \begin{bmatrix} y_{\mathrm{H}k} \\ y_{\mathrm{V}k} \end{bmatrix} = \sqrt{P} \begin{bmatrix} f_{\mathrm{H}}(\theta,\varphi)\cos\gamma_k \\ f_{\mathrm{V}}(\theta,\varphi)\sin\gamma_k e^{j\eta_k} \end{bmatrix} + \mathbf{n}_k \quad (2)$$

where P is the transmit power; $\mathbf{n}_k = \begin{bmatrix} n_{\mathrm{H}k} \\ n_{\mathrm{V}k} \end{bmatrix}$ denotes the noise vector with the probability density function (PDF) as $\mathcal{CN}\left(0, \sigma^2 \mathbf{I}_{2\times 2}\right)$. Then, in order to recover the information carried by the PS, the polarization parameters are demodulated as

$$\begin{aligned} \gamma_{\mathrm{R}k} &= \arctan\left(\frac{\mathrm{abs}(y_{\mathrm{V}k})}{\mathrm{abs}(y_{\mathrm{H}k})}\right) \\ \eta_{\mathrm{R}k} &= \Xi(y_{\mathrm{V}k}) - \Xi(y_{\mathrm{H}k}) \end{aligned} \quad (3)$$

If ignoring the noise effect, it is obtained

$$\gamma_{\mathrm{R}k} = \arctan\left(\frac{\mathrm{abs}\left(f_{\mathrm{V}}(\theta,\varphi)\right)}{\mathrm{abs}\left(f_{\mathrm{H}}(\theta,\varphi)\right)} \tan\gamma_k\right) \quad (4)$$

For a traditional transmitter, it is obtained $f_{\mathrm{V}}(\theta,\varphi) = f_{\mathrm{H}}(\theta,\varphi)$ in all directions. Then, base on Eq.(3), it is obtained $\gamma_{\mathrm{R}k} = \gamma_k$ and $\eta_{\mathrm{R}k} = \eta_k$. Thus, the same PS of the signal can be demodulated in arbitrary directions, which is possible for an eavesdropper to recover the information in undesired directions. In this paper, to over the problem, a transmission method base on time-varying array and polarization filtering is proposed to enhance the information security, which is detailed described in next parts.

4. Principle of the proposed method

4.1 Signal modulation and demodulation

In the proposed method, the information is divided into two parts: I_1 and I_2 as shown in Figure 2, which are respectively modulated into amplitude-phase symbols $\mathbf{x}_1$ and $\mathbf{x}_2$ with length K. Then, two orthogonal PS ($\mathbf{P}_1$ and $\mathbf{P}_2$) are multiply with them respectively, which obtains the signals as

$$\mathbf{P}_1\mathbf{x}_1 + \mathbf{P}_2\mathbf{x}_2 = \begin{bmatrix} \mathbf{x}_{\mathrm{H}}^t \\ \mathbf{x}_{\mathrm{V}}^t \end{bmatrix} \quad (5)$$

where

$$\begin{aligned}\mathbf{x}_1 &= [x_{11}, x_{12}, \cdots, x_{1K}] \\ \mathbf{x}_2 &= [x_{21}, x_{22}, \cdots, x_{2K}]\end{aligned} \tag{6}$$

Then, we obtain transmit signals as

$$\begin{aligned}\mathbf{x}^t &= \sqrt{P}\begin{bmatrix} f_{\mathrm{H}}(\theta)\mathbf{x}_{\mathrm{H}}^t \\ f_{\mathrm{V}}(\theta)\mathbf{x}_{\mathrm{V}}^t \end{bmatrix} \\ &= \sqrt{P}\left(\begin{bmatrix} f_{\mathrm{H}}(\theta)\cos\gamma_1 \\ f_{\mathrm{V}}(\theta)\sin\gamma_1 e^{j\eta_1} \end{bmatrix}\mathbf{x}_1 + \begin{bmatrix} f_{\mathrm{H}}(\theta)\cos\gamma_2 \\ f_{\mathrm{V}}(\theta)\sin\gamma_2 e^{j\eta_2} \end{bmatrix}\mathbf{x}_2\right)\end{aligned} \tag{7}$$

For legal users with direction θ_d, the beam gains $f_{\mathrm{H}}(\theta_d)=f_{\mathrm{V}}(\theta_d)=f(\theta_d)$. Then, the received signals are written as

$$\mathbf{y} = \sqrt{P}f(\theta_d)\left(\begin{bmatrix} \cos\gamma_1 \\ \sin\gamma_1 e^{j\eta_1} \end{bmatrix}\mathbf{x}_1 + \begin{bmatrix} \cos\gamma_2 \\ \sin\gamma_2 e^{j\eta_2} \end{bmatrix}\mathbf{x}_2\right) + \mathbf{n} \tag{8}$$

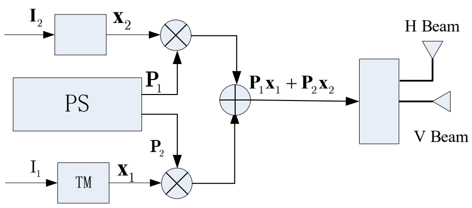


Figure 2 Diagram of signal processing at the transmit side

To recover the information conveyed by $\mathbf{x}_1$ and $\mathbf{x}_2$, two signal matrices should be separated firstly.

4.2 Signal separation base on polarization filtering

To separation two signals, polarization filtering matrix is constructed base on the PSs of two signals ($\mathbf{P}_1$ and $\mathbf{P}_2$) as,

$$\begin{aligned}\mathbf{Q}_1 &= \mathbf{P}_1\left((\mathbf{P}_1)^{\mathbf{H}} P_{\mathbf{P}_2}^{\perp}\mathbf{P}_1\right)^{-1}(\mathbf{P}_1)^{\mathbf{H}} P_{\mathbf{P}_2}^{\perp} \\ \mathbf{Q}_2 &= \mathbf{P}_2\left((\mathbf{P}_2)^{\mathbf{H}} P_{\mathbf{P}_1}^{\perp}\mathbf{P}_l^k\right)^{-1}\left(\mathbf{P}_l^k\right)^{\mathbf{H}} P_{\mathbf{P}_1}^{\perp}\end{aligned} \tag{9}$$

where

$$\begin{aligned}P_{\mathbf{P}_2}^{\perp} &= \mathbf{E}\text{-}\mathbf{P}_2\left((\mathbf{P}_2)^{\mathbf{H}}\mathbf{P}_2\right)^{-1}(\mathbf{P}_2)^{\mathbf{H}} \\ P_{\mathbf{P}_1}^{\perp} &= \mathbf{E}\text{-}\mathbf{P}_1\left((\mathbf{P}_1)^{\mathbf{H}}\mathbf{P}_1\right)^{-1}(\mathbf{P}_1)^{\mathbf{H}}\end{aligned} \tag{10}$$

As described in[15, 16], it could be derived that

$$\begin{aligned}&\mathbf{Q}_1\mathbf{P}_1 = \mathbf{P}_1, \mathbf{Q}_1\mathbf{P}_2 = \mathbf{0} \\ &\mathbf{Q}_2\mathbf{P}_2 = \mathbf{P}_2, \mathbf{Q}_2\mathbf{P}_1 = \mathbf{0}\end{aligned} \tag{11}$$

Then, with $\mathbf{Q}_1$ and $\mathbf{Q}_2$, two signals can be obtained by

$$\begin{aligned}\mathbf{Q}_1\mathbf{y} &= \sqrt{P}f_{\mathrm{H}}(\theta_d)\mathbf{x}_1 + \mathbf{Q}_1\mathbf{n} \\ \mathbf{Q}_2\mathbf{y} &= \sqrt{P}f_{\mathrm{H}}(\theta_d)\mathbf{x}_2 + \mathbf{Q}_2\mathbf{n}\end{aligned} \tag{12}$$

In addition, according to Eq.(12), the noise power is represented as ($\mathbf{Q}_1\mathbf{n}$ is taken for an example)

$$\tilde{\sigma}^2 = trace\left(\mathbf{Q}_1(\mathbf{Q}_1)^{\mathrm{H}}\sigma^2\right) = \frac{\sigma^2}{\sin^2\varpi} \tag{13}$$

ϖ denotes the principal angle between subspace $\mathbf{Q}_1$ and $\mathbf{Q}_2$ on Poincare sphere [14]. It is found that $\sin^2\xi \le 1$ and the ideal condition is $\varpi = \frac{\pi}{2}$, in which case the noise power is not amplified. Therefore, the polarization parameters for both PSs should satisfy the follow requirement,

$$\gamma_1 = \frac{\pi}{2} - \gamma_2, \eta_1 = \pi + \eta_2 \tag{14}$$

In this manner, the noise power is not amplified. Then, both two signals can be further demodulated separately base on the Maximum likelihood estimation algorithm.

For Bob, the PSs of two signals are shared with the transmitter, the polarization filtering matrix can be constructed smoothly. However, for Eve, to recover the information, it is necessary to crack the PSs of two signals for signal separation. Although the number of PSs is endless, the PSs are still possibly cracked. In order to further improve the transmission security, the time-varying array method is proposed to design two beams, which makes the gains are designed equal to each other in the desired direction, while different in other directions. In this manner, the PSs vary in undesired directions, which make it difficult to crack the PSs. Thus, improve the transmission security.

4.3 Beams design base on time-varying array

Base on the array shown in Figure 1, the channel vector for both polarizations can be denoted as

$$\mathbf{h}_\theta = \left[e^{-j\frac{2\pi d(N-1)}{2\lambda}\sin(\theta)}, e^{-j\frac{2\pi d(N-3)}{2\lambda}\sin(\theta)}, \cdots, e^{j\frac{2\pi d(N-1)}{2\lambda}\sin(\theta)} \right]^{\mathrm{T}} \tag{15}$$

It is found that $\mathbf{h}_\theta$ has a particular property that half of its elements are a complex conjugate of the other half, for example, $\mathbf{h}_\theta = \left[h_1, 1, h_1^*\right]^{\mathrm{T}}$ for N=3 and $\mathbf{h}_\theta = \left[h_1, h_2, h_2^*, h_1^*\right]^{\mathrm{T}}$ for $N = 4$. Thus, in normal condition, two beams can be represented as

$$\begin{aligned} f_{\mathrm{H}}(\theta) &= \mathbf{h}_\theta^{\mathrm{H}} \mathbf{w}_{\mathrm{H}} = \mathbf{h}_\theta^{\mathrm{H}} \mathbf{h}_{\theta_d} \\ f_{\mathrm{V}}(\theta) &= \mathbf{h}_\theta^{\mathrm{H}} \mathbf{w}_{\mathrm{V}} = \mathbf{h}_\theta^{\mathrm{H}} \mathbf{h}_{\theta_d} \end{aligned} \tag{16}$$

where θ_d denotes the desired direction. It is found that both $f_{\mathrm{H}}(\theta)$ and $f_{\mathrm{V}}(\theta)$ are real numbers in all directions, which means the signals received by Bob and Eve convey the same information and the only difference is the signals' power. So, if the eavesdropper is sensitive enough, it is possible to crack the PSs of two signals. To over this problem and improve the transmission security, in the proposed, $f_{\mathrm{H}}(\theta)$ and $f_{\mathrm{V}}(\theta)$ are designed base on time-varying array method to distorted the amplitude and phase of signals in undesired directions. The detailed steps are as follows,

At first, two vectors are generated to set some elements of the beamforming vectors to zero as

$$\mathbf{w}_{\mathrm{H}} = \frac{1}{L}\mathbf{u}_{\mathrm{H}} \odot \mathbf{h}_{\theta_d}, \mathbf{w}_{\mathrm{V}} = \frac{1}{L}\mathbf{u}_{\mathrm{V}} \odot \mathbf{h}_{\theta_d} \tag{17}$$

where $\mathbf{u}_{\mathrm{H}}$ and $\mathbf{u}_{\mathrm{V}}$ are two $N \times 1$ vectors with elements 0 or 1 and $L = \sum_{n=1}^{N} \mathbf{u}_{\mathrm{O}}(n) < N, \mathrm{o} = \mathrm{H}, \mathrm{V}$; $\odot$ represents the Hadamard product. (In this paper, we just consider the same L for $\mathbf{u}_{\mathrm{H}}$ and $\mathbf{u}_{\mathrm{V}}$).

If the azimuth angle $\theta = \theta_d$, $f_{\mathrm{H}}(\theta)$ equals $f_{\mathrm{V}}(\theta)$ and they are still real numbers. However, when $\theta \ne \theta_d$, $f_{\mathrm{H}}(\theta)$ and $f_{\mathrm{V}}(\theta)$ are no longer real numbers and their amplitudes are no longer equal [17]. For example, in the case that N=5, L=4, $\mathbf{c}_{\mathrm{H}} = [0,1,1,1,1]^{\mathrm{T}}, \mathbf{c}_{\mathrm{V}} = [1,0,1,1,1]^{\mathrm{T}}$, then

$$\tilde{\mathbf{w}}_{\mathrm{H}}=\frac{1}{L}\left[0,\mathbf{h}_{\theta_d}(2),1,\mathbf{h}^*_{\theta_d}(2),\mathbf{h}^*_{\theta_d}(1)\right]^{\mathrm{T}}$$
$$\tilde{\mathbf{w}}_{\mathrm{V}}=\frac{1}{L}\left[\mathbf{h}_{\theta_d}(1),0,1,\mathbf{h}^*_{\theta_d}(2),\mathbf{h}^*_{\theta_d}(1)\right]^{\mathrm{T}} \tag{18}$$

Two beams can be further written as

$$\begin{aligned}
f_{\mathrm{H}}(\theta)&=\mathbf{h}_\theta^{\mathrm{H}}\tilde{\mathbf{w}}_{\mathrm{H}}\\
&=\frac{1}{4}\left[\begin{array}{l}\underbrace{\mathbf{h}^*_\theta(2)\mathbf{h}_{\theta_d}(2)+\mathbf{h}_\theta(2)\mathbf{h}^*_{\theta_d}(2)+1}_{real}\\ \underbrace{+0+\mathbf{h}_\theta(1)\mathbf{h}^*_{\theta_d}(1)}_{complex}\end{array}\right]\\
f_{\mathrm{V}}(\theta)&=\mathbf{h}_\theta^{\mathrm{H}}\tilde{\mathbf{w}}_{\mathrm{V}}\\
&=\frac{1}{4}\left[\begin{array}{l}\underbrace{\mathbf{h}^*_\theta(1)\mathbf{h}_{\theta_d}(1)+\mathbf{h}_\theta(1)\mathbf{h}^*_{\theta_d}(1)+1}_{real}\\ \underbrace{+0+\mathbf{h}_\theta(2)\mathbf{h}^*_{\theta_d}(2)}_{complex}\end{array}\right]
\end{aligned} \tag{19}$$

According to Eq.(19), it is found that $f_{\mathrm{H}}(\theta)$ and $f_{\mathrm{V}}(\theta)$ are no longer real numbers. The amplitude and phase of two beams vary along with $\mathbf{u}_{\mathrm{H}}$ and $\mathbf{u}_{\mathrm{V}}$. In this condition, the first signals $\mathbf{x}_1$ are taken for an example, the polarization parameters are represented as

$$\begin{aligned}
\gamma_1^{\mathrm{R}}&=\arctan\left(\left|\frac{f_{\mathrm{V}}(\theta)}{f_{\mathrm{H}}(\theta)}\right|\tan\gamma_1\right)\\
\eta_1^{\mathrm{R}}&=\psi\left(f_{\mathrm{V}}(\theta)\right)-\psi\left(f_{\mathrm{H}}(\theta)\right)+\eta_1
\end{aligned} \tag{20}$$

where $\psi(\bullet)$ denotes the phase acquisition operation. The polarization constellation transformation caused by two beams is shown in Figure 3. Without loss of generality，it is assumed that $\left|\frac{f_{\mathrm{V}}(\theta)}{f_{\mathrm{H}}(\theta)}\right|>1$ and the original constellation point is represented as P1. When $\eta_1^{\mathrm{R}}\neq\eta_1$, the constellation point is rotated and transformed into $\mathrm{P}_1^{\mathrm{R}}$; when $\gamma_1^{\mathrm{R}}\neq\gamma_1$, $\mathrm{P}_1^{\mathrm{R}}$ will move toward the horizontal polarization state P_{H} and transform into P_g.

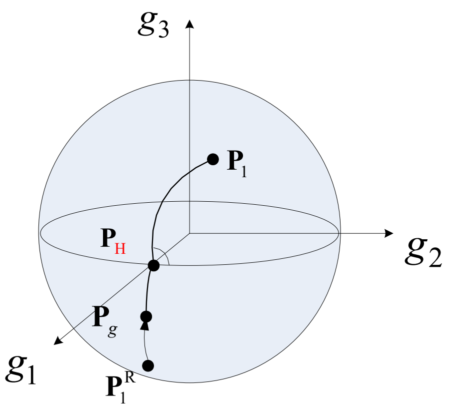


Figure 3 Polarization Constellation Transformation

In this manner, when two beam gains vary randomly, the PSs of two polarization signals vary dynamically, which make PSs difficult for eavesdroppers to crack. Thus, the polarization filtering matrix can not be correctly constructed to separate two signals, which leads to the appearance of the mutual interferences. Therefore, the transmission security is enhanced.

On the other hand, in the case that the eavesdropper obtains the PSs of the signals and the right polarization filtering matrices $\mathbf{Q}_1$ and $\mathbf{Q}_2$ are constructed. As signals in undesired directions vary dynamically, the PSs changed into $\overline{\mathbf{P}}_1$ and $\overline{\mathbf{P}}_2$, we obtain

$$\begin{aligned}\mathbf{Q}_1\overline{\mathbf{P}}_1 \neq \mathbf{P}_1, \mathbf{Q}_1\overline{\mathbf{P}}_2 \neq \mathbf{0} \\ \mathbf{Q}_2\overline{\mathbf{P}}_2 \neq \mathbf{P}_2, \mathbf{Q}_2\overline{\mathbf{P}}_1 \neq \mathbf{0}\end{aligned} \tag{21}$$

According to Eq.(21), it found that the two signals can not be separated, thus, the mutual interferences between them appears.

Above all, with the proposed method, the signals in undesired directions distort and the PSs are difficult to crack. Thus, the transmission information is well protected and a secure link is formed.

For the legitimate users, based on Eq.(20), According to the maximum likelihood judgment criterion, by comparing the receiving polarization state Q_{R}^k to the sending polarization state $\{Q_{\mathrm{T}}^m\}_{m=1}^M$, through choosing the polarization state with the smallest spherical distance as the output polarization state , for example, we assume

$$Q_l = \min_{1\le m\le M} \mathrm{dis}\left(Q_{\mathrm{R}}^k, Q_{\mathrm{T}}^m\right) \tag{22}$$

where $\mathrm{dis}\left(x_1, x_2\right)$ denotes the spherical distance between x_1 and x_2 on the Poincare sphere. Under the influence of noise, the constellation point of the received polarization signals will shift from the center of the original polarization constellation point on the Poincare sphere, and the position probability density function of the receiving polarization constellation point can be calculated by $f\left(t_i, \varphi_i\right)$, which can be calculated

$$f\left(t_i, \varphi_i\right) = \frac{\sin t_i}{4\pi} e^{-\xi_{\mathrm{B}}(1-\cos t_i)/2}\left[1+\xi_{\mathrm{B}}\left(1+\cos t_i\right)/2\right] \tag{23}$$

where t_i, φ_i are the corresponding longitude and latitude of Q_{R}^i on the sphere as shown in , respectively. Then the symbol error rate can be calculated as shown in Figure 4.

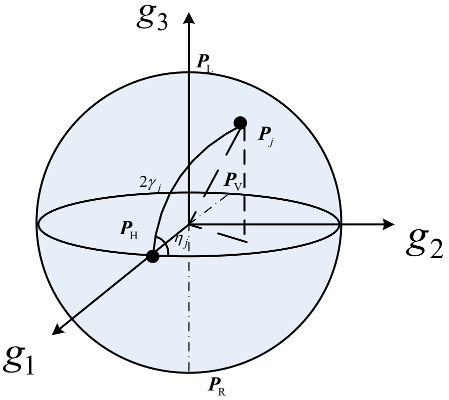


Figure 4 Diagram of the polarization-state demodulation

$$G_{SER} = \frac{1}{M}\sum_{i=1}^{M} g_i \tag{24}$$

$$g_i = \begin{cases} \left[\begin{array}{l} \int_{\pi-\vartheta_0}^{\pi} \int_0^{2\pi} f\left(t_i,\varphi_i\right) d\varphi_i dt_i + \\ \int_{\vartheta_0}^{\pi-\vartheta_0} \int_0^{\alpha(\vartheta_0,t_i)} f\left(t_i,\varphi_i\right) d\varphi_i dt_i \end{array} \right], M=2 \\ \sum_{j=1}^{k} 2 \left[\begin{array}{l} \int_{\psi_{ij}}^{\pi} \int_0^{\alpha(\vartheta_0,\psi_{ij})} f\left(t_i,\varphi_i\right) d\varphi_i dt_i + \\ \int_{\vartheta_0}^{\psi_{ij}} \int_0^{\alpha(\vartheta_0,t_i)} f\left(t_i,\varphi_i\right) d\varphi_i dt_i \end{array} \right], M>2 \end{cases} \tag{25}$$

where $\alpha\left(\vartheta_0,t_i\right)$ can be calculated by (26), ϑ_0 denotes the half of the spherical distance of the initial adjacent constellation point, and ψ_{ij} denotes the distance between the constellation point Q_{R}^i and the boundary point of the determination area, which can be calculated by Eq(27) as

$$\alpha\left(\vartheta_0,t_i\right) = \arccos(\tan\vartheta_0/t_i) \tag{26}$$

$$\begin{cases} \psi_{i1} = 2\gamma_{\mathrm{R}}^i, \psi_{i2} = \pi - 2\gamma_{\mathrm{R}}^i, \left(M=4; i\in[1,4]\right); k=2 \\ \psi_{i1} = \psi_{i2} = \arccos\left[\dfrac{\cos 2\gamma_{\mathrm{R}}^i + \sin 2\gamma_{\mathrm{R}}^i \tan\left(\gamma_{\mathrm{R}}^i + \gamma_{\mathrm{R}}^{i+M/2}\right)}{1+\sec^2(o/2)\tan^2\left(\gamma_{\mathrm{R}}^i + \gamma_{\mathrm{R}}^{i+M/2}\right)}\right] \\ \psi_{i3} = 2\gamma_{\mathrm{R}}^i, \left(M\geq 8; i\in[1,M/2]\right); k=3 \\ \psi_{i1} = \psi_{i2} = \arccos\left[\dfrac{\cos\left(\gamma_{\mathrm{R}}^i - \gamma_{\mathrm{R}}^{i-M/2}\right)}{1+\sin^2\left(\gamma_{\mathrm{R}}^i + \gamma_{\mathrm{R}}^{i+M/2}\right)\tan^2(o/2)}\right] \\ \psi_{i3} = \pi - 2\gamma_{\mathrm{R}}^i, \left(M\geq 8; i\in[1,M/2]\right); k=3 \end{cases} \tag{27}$$

where o denotes the spherical angle $\angle Q_{\mathrm{R}}^i Q_{\mathrm{H}} Q_{\mathrm{R}}^j$, which can be calculated as

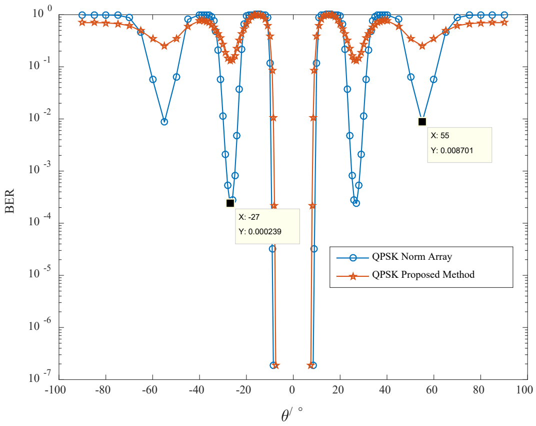
$$o=\angle Q_{\mathrm{R}}^i Q_{\mathrm{H}} Q_{\mathrm{R}}^j = 2\arcsin\left[\sin\left(\vartheta_0\right)/\sin\left(2\gamma_i\right)\right] \tag{28}$$

5. Simulation results

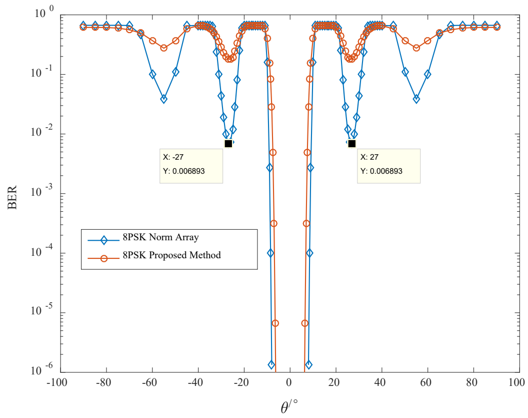
In this section, the simulations are performed to evaluate the security performance of the proposed method based on Matlab. A 11-element planar phased array is assumed and the transmitting frequency is 23GHz. quad-phase shift key (QPSK) and 8PSK are considered to modulate two information sequences, then, $\mathbf{x}_1$ is QPSK signal and $\mathbf{x}_2$ is 8PSK signal. In addition, similar results are similar with other modulation orders. Here, it is worth to notice that with a high communication frequency, the wavelength is small and a large number of antenna elements can be densely arranged, which results into a very narrow main lobe. So, in this study, we only consider the side lobe eavesdropper.

At first, the signal to noise ratio in the desired direction 0° is set to 25dB and $\mathbf{u}_{\mathrm{H}}$, $\mathbf{u}_{\mathrm{V}}$ updates every 20 symbol time. We compare the BER performance of the proposed method with the method based on randomly vary array and the normal array versus azimuth angle. Figure 5 gives the BER curves of both two methods. It is found that in the desired direction 0°both two methods can achieve a small bit error rate, which demonstrates the effectiveness of the proposed scheme. While in side lobes, such as $\theta=\pm 27°,\pm 55°$, for QPSK signals, with the normal array, the bit error rate is 10^{-4} and 10^{-2}; for 8PSK signals, when $\theta=\pm 27°$, the bit error rate is 10^{-2}, it is possible for eavesdropper to crack the signals in these directions. However, with the proposed method, the BER is bigger, it is mainly because the signal in side lobes are distorted due to the changing $\mathbf{u}_{\mathrm{H}}$, $\mathbf{u}_{\mathrm{V}}$. In this way, the signals'

PS is difficult to crack, thus two signals can not be separated and a good protection for signals is provided. When the directions is set to 10°, the similar conclusions can be gotten as shown in figure 6.

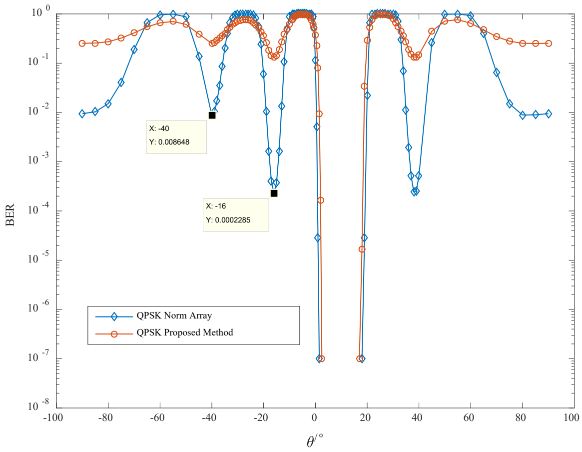


(a) BER performance of the first signals (0°)

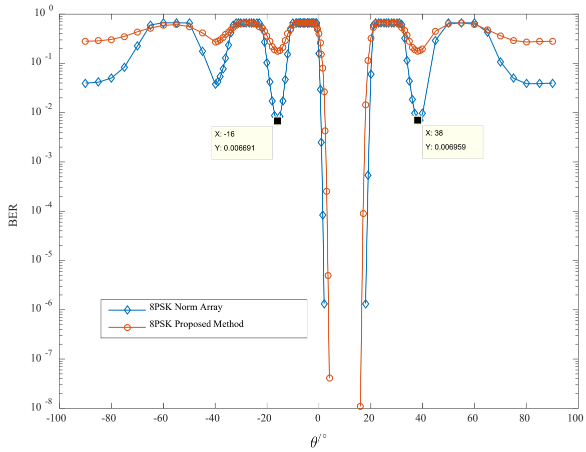


(b) BER performance of the second signals (0°)

Figure 5 BER performance comparison versus azimuth angle (0°)



(a) BER performance of the first signals (10°)

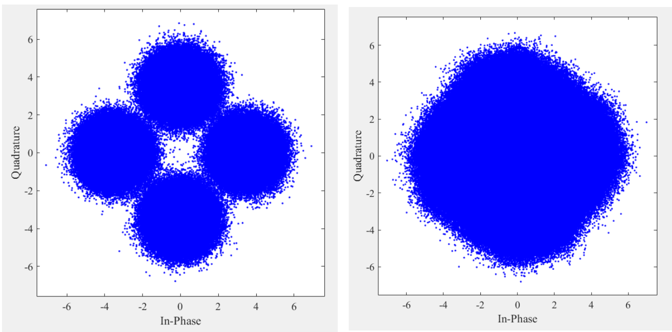


(b) BER performance of the first signals (10°)

Figure 6 BER performance comparison versus azimuth angle (10°)

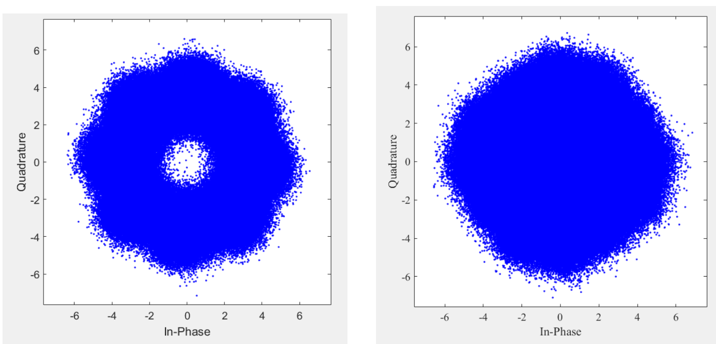
In this simulation, we assume Eavesdroppers can obtained two PSs of two signals. After polarization filtering, two signals are separated and Figure 7 and Figure 8 shows the constellations comparison of the norm array and the proposed method in the azimuth angle 27° (the desired direction is 0°) . It is found that from Figure 7 (a) and Figure 8(a) that with the normal array, the QPSK constellation is clear and the 8PSK constellation is a little worse. However, when the SNR is bigger enough, the 8PSK constellation will be also clear, which would cause the information leakage.

With the proposed, the constellations of both the QPSK and 8PSK are distorted, which is difficult to recover the information as shown in Figure 7 (b) and Figure 8(b), thus offers a good protection.



(a) Normal array (b) Proposed method

Figure 7 QPSK constellation comparison of the proposed method and the normal array with the azimuth angle 27°



(a) Normal array (b) Proposed method

Figure 8 8PSK constellation comparison of the proposed method and the normal array with the azimuth angle 27°

6. Conclusion

This paper puts forwards a secure transmission method base on time-varying array and polarization filtering is proposed to enhance the information security in wireless communications. With the method, the signals can be totally separated in the desired direction and demodulated separately. While the constellation is distorted in undesired directions, which makes it difficult to recover the information. In addition, the distorted constellations are also vary dynamically. Thus, a secure link can be formed. With the proposed method, the security can be ensured.

Acknowledgment

This work was supported by Fund of Complex System Simulation Laboratory (6142401004032106).

References

[1] S. Elmeadawy and R. M. Shubair, "6G Wireless Communications: Future Technologies and Research Challenges," in *2019 International Conference on Electrical and Computing Technologies and Applications (ICECTA)*, 2019, pp. 1-5.

[2] Z. Luo, Z. Pei, C. Yang, Z. Liu, and H. Chen, "Secure Image Signal Transmission Scheme Using Poly-Polarization Filtering and Orthogonal Matrix," *APPLIED SCIENCES-BASEL,* vol. 13, 2023 FEB 2023.

[3] J. An and K. Liu, A Bayes Decision Approach to Enhance MIMO Wireless System Performance, *IEICE Proceedings Series*. 2022.

[4] H. Guo, D. Y. Zhang, Y. Juan, Z. Ding, and J. He, "A Hybrid-fed Dual-polarized Patch Antenna with Metasurface Coverage for 5G Applications," *Progress In Electromagnetics Research Letters,* 2023.

[5] K. P. Liolis, Go, x, V. Mez, x, J.*, et al.*, "Statistical Modeling of Dual-Polarized MIMO Land Mobile Satellite Channels," *IEEE Transactions on Communications,* vol. 58, pp. 3077-3083, September 2010.

[6] Z. Luo, H. Wang, and H. Hao, "A Spectrum Efficient Spatial Polarized QAM Modulation Scheme for Physical Layer Security in Dual-Polarized Satellite Systems," *Ieice Transactions on Communications,* vol. 101, pp. 146-153, 2018.

[7] Z. K. Luo, Z. M. Pei, and B. Zou, "Polarization Filtering Based Transmission Scheme for Wireless Communications," *Ieice Transactions on Fundamentals of Electronics Communications and Computer Sciences,* vol. E102A, pp. 1387-1392, Oct 2019.

[8] W. Dong, Z. Meng, F. Wei, and H. Weiqing, "A spectrum efficient polarized PSK/QAM scheme in the wireless channel with polarization dependent loss effect," in *22nd International Conference on Telecommunications (ICT)*, Sydney, NSW, Australia, 2015, pp. 249-255.

[9] Z. Luo, H. Wang, and K. Zhou, "Polarization Filtering Based Physical-Layer Secure Transmission Scheme for Dual-Polarized Satellite Communication," *IEEE Access,* vol. 5, pp. 24706-24715, 2017.

[10] M. Hafez, M. Yusuf, T. Khattab, T. Elfouly, and H. Arslan, "Secure Spatial Multiple Access Using Directional Modulation," *IEEE Transactions on Wireless Communications,* vol. PP, pp. 1-1, 2017.

[11] L. Huang, J. Zhang, X. Xu, and Z. Ye, "Robust Adaptive Beamforming With a Novel Interference-Plus-Noise Covariance Matrix Reconstruction Method," *Ieee Transactions on Signal Processing,* vol. 63, pp. 1643-1650, Apr 1 2015.

[12] M. P. Daly and J. T. Bernhard, "Directional Modulation Technique for Phased Arrays," *IEEE*

Transactions on Antennas and Propagation, vol. 57, pp. 2633-2640, 2009.

[13] Z. Luo, H. Wang, K. Zhou, and W. Lv, "Combined Constellation Rotation With Weighted FRFT for Secure Transmission in Polarization Modulation Based Dual-Polarized Satellite Communications," *IEEE Access,* vol. 5, pp. 27061-27073, 2017.

[14] Z. Wen, F. Chunyan, L. Fangfang, and G. Caili, "Polarization oblique projection based self-interference cancellation against PA nonlinear distortion in MIMO full duplex system," *China Communications,* vol. 13, pp. 49-59, 2016.

[15] B. Cao, Q. Y. Zhang, D. Liang, S. M. Wen, L. Jin, and Y. Q. Zhang, "Blind Adaptive Polarization Filtering Based on Oblique Projection," in *2010 IEEE International Conference on Communications (ICC)*, Cape Town, South Africa, 2010, pp. 1-5.

[16] R. T. Behrens and L. L. Scharf, "Signal processing applications of oblique projection operators," *IEEE Transactions on Signal Processing,* vol. 42, pp. 1413-1424, 1994.

[17] N. N. Alotaibi and K. A. Hamdi, "Switched Phased-Array Transmission Architecture for Secure Millimeter-Wave Wireless Communication," *IEEE Transactions on Communications,* vol. 64, pp. 1303-1312, 2016.