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• **LETTER** •

Polarized Spatial and Directional Modulation Toward Secure Wireless Transmission

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Dear editor,

Directional modulation (DM) has been developed as a promising physical layer security (PLS) technique for transmitting undistorted signals into a predefined direction while twisting constellation formats in undesired directions. However, most of the DM techniques cannot guarantee transmission security when eavesdropper and legitimate user share the same direction. In order to tackle this problem, a DM system with multiple distributed and cooperative receivers, namely DM-CR, was proposed in [1]. Then the DM-CR and spatial modulation (SM) techniques were combined into a novel directional modulation (SDM) system [2], which not only maintains the secure transmission in DM-CR systems but also possesses SM's high-throughput characteristics.

Recently, polarization states (PS) of electromagnetic waves, as a new dimension in addition to frequency, time, and amplitude-phase, have been explored as a novel modulation scheme termed polarization modulation (PM) [3–5]. Motivated by the PM system, a polarized spatial and directional modulation (PSDM) scheme is proposed in this paper to improve the security and spectral efficiency of SDM without increasing the number of RF chains.

Transceiver design. As shown in Figure 1(a), we consider N_r distributed cooperative receivers at Bob as well as a eavesdropper Eve both equipped with a single dual-polarized (DP) antenna. The DP antenna consisting of a pair of co-located orthogonally polarized dipoles is capable of transmitting the horizontal and vertical components of signals, denoted as E_h and E_v [6]. Furthermore, arbitrary polarization states (γ, η) can be shaped by different combinations of the E_h and E_v, which are given by

$$\begin{aligned} \gamma &= \arctan(\tfrac{E_v}{E_h}), \\ \eta &= \text{angle}(E_v) - \text{angle}(E_h), \end{aligned} \tag{1}$$

where $\gamma \in [0, \pi/2]$ is auxiliary polarisation angle and $\eta \in [-\pi, \pi)$ is polarization phase difference. In the remainder of this article, all antennas are defaulted as the same DP antenna. Additionally, the legitimate transmitter Alice is equipped with a polarization-sensitive crossed-dipole array consisting of N_t DP antennas. Suppose the directions of Bob and Eve relative to Alice are denoted as $\boldsymbol{\theta}_B = \left[\theta_{B_1}, \theta_{B_2}, \cdots, \theta_{B_{N_r}}\right]$ and θ_E respectively. Furthermore, all of the Bob's antennas are connected to a central digital signal processing (DSP) unit which operates the detection and demodulation of receive signals jointly. In the real transmission, even if the receiver is equipped with the same antenna as the transmitter, there exists mutual interference between receive signals, $\tilde{E}_h$ and $\tilde{E}_y$, owing to the cross-polar discrimination (XPD) [7]. Therefore, the receive signals are given by

$$\begin{bmatrix} \tilde{E}_h \\ \tilde{E}_v \end{bmatrix} = \boldsymbol{\chi} \begin{bmatrix} E_h \\ E_v \end{bmatrix} = \begin{bmatrix} 1 & \sqrt{\chi} \\ \sqrt{\chi} & 1 \end{bmatrix} \begin{bmatrix} E_h \\ E_v \end{bmatrix}, \tag{2}$$

where $\boldsymbol{\chi}$ is the coupling matrix and the XPD parameter in dB is denoted as $\chi_{dB}^{-1} = -10 \log \chi$. Assuming the transceiver is located in the same plane and taking the XPD into consideration, the steering array in azimuth angle θ, $\mathbf{H}_p^H(\theta) \in \mathbb{C}^{2 \times 2N_t}$, is formulated as

$$\mathbf{H}_p^H(\theta) = \frac{1}{\sqrt{(1+\chi)}} \mathbf{h}_s^H(\theta) \otimes \boldsymbol{\chi}, \tag{3}$$

where $\otimes$ denotes the Kronecker product, and $\mathbf{h}_s(\theta) \in \mathbb{C}^{N_t \times 1}$ is the steering vector of the normal uniform linear array, expressed as

$$\mathbf{h}_s(\theta) = \left[\, 1, \ e^{j\pi \sin\theta}, \ \cdots, \ e^{j(N_t-1)\pi \sin\theta} \,\right]^T. \tag{4}$$

Then, considering all the N_r receivers, the steering matrix of Bob $\mathbf{H}_B \in \mathbb{C}^{2N_r \times 2N_t}$ can be further expressed as

$$\mathbf{H}_B = \left[\, \mathbf{H}_p^H(\theta_{B_1}) \ \mathbf{H}_p^H(\theta_{B_2}) \ \cdots \ \mathbf{H}_p^H(\theta_{B_{N_r}}) \,\right]^T. \tag{5}$$

At the transmitter side, the total $\log_2(MPN_r)$ data bits are divided into three parts, where the first $\log_2(M)$ bits are invoked to generate the M-order amplitude-phase modulation (APM) symbol s_m, the $\log_2(P)$ bits of the second part are used to choose one polarization state $(\gamma, \eta)_p$ from the P-elements polarization state set, and the remaining $\log_2(N_r)$

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bits are allocated to select the target index l of the receive antenna. Thus, the transmit vector $\mathbf{s}_{mpl} \in \mathbb{C}^{2N_r \times 1}$ is given by

$$\begin{aligned}\mathbf{s}_{mpl} &= \mathbf{e}_l \otimes \begin{bmatrix} \cos\gamma_p b_m \\ \sin\gamma_p e^{j\eta_p} b_m \end{bmatrix} \\ &= [\underbrace{0,0}_{1\text{th}}, \cdots, 0, \underbrace{\cos\gamma_p b_m, \sin\gamma_p e^{j\eta_p} b_m}_{l\text{th}}, 0, \cdots, \underbrace{0,0}_{N_r\text{th}}]^T,\end{aligned} \tag{6}$$

where $b_m \in \mathcal{B} = \{b_1, b_2, \cdots, b_M\}$ is the APM symbol with uniform power (i.e., $\mathbb{E}\{|b_m|^2 = 1\}$), then $(\cos\gamma_p, \sin\gamma_p e^{j\eta_p}) \in \mathcal{P}$ is the PM symbol, and $\mathbf{e}_l$ is the lth standard basis column vector of the $\mathbf{I}_{N_r}$. Furthermore, the beamforming vector for the ith receiver of Bob, denoted as $\mathbf{W}_{B_i} \in \mathbb{C}^{2N_t \times 2}$, $i = 1 \sim N_r$, is formulated as

$$\mathbf{W}_{B_i} = \left[\mathbf{h}_s(\theta_{Bi}) \otimes \begin{bmatrix} \alpha_i \\ 0 \end{bmatrix}, \mathbf{h}_s(\theta_{Bi}) \otimes \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right], \tag{7}$$

where $\alpha_i = e^{j\phi_i} \in \mathcal{A}$, $i = 1 \sim N_r$ is a scrambling factor updated with the symbol rate, which is available at both Alice and Bob. Taking all the antennas of Bob into consideration, the beamforming vector $\mathbf{W} \in \mathbb{C}^{2N_t \times 2N_r}$ can be expressed as

$$\mathbf{W} = \left[\mathbf{W}_{B_1}, \mathbf{W}_{B_2}, \cdots \mathbf{W}_{B_{N_r}} \right]. \tag{8}$$

Signal Detection. Therefore, the N_r pairs of receive signal $\mathbf{y}_B \in \mathbb{C}^{2N_r \times 1}$ at Bob can be expressed as

$$\mathbf{y}_B = \mathbf{H}_B \mathbf{W} \mathbf{s}_{mpl} + \mathbf{n}_B, \tag{9}$$

where $\mathbf{n}_B \in \mathbb{C}^{2N_r \times 1}$ is the additive white Gaussian noise (AWGN) at Bob, each element of which obeys $\mathcal{CN}(0, \sigma_B^2)$. Furthermore, the APM symbol b_m, PM symbol $(\cos\gamma_p, \sin\gamma e^{j\eta_p})$, and receiver index l can be jointly detected by the maximum likelihood (ML) criterion as

$$(\hat{m}, \hat{p}, \hat{l}) = \underset{m,p,l}{\arg\min} \left\| \mathbf{y}_B - \mathbf{H}_B \mathbf{W} \mathbf{s}_{mpl} \right\|_2^2. \tag{10}$$

Similarly, the receive signal $\mathbf{y}_E \in \mathbb{C}^{2 \times 1}$ at Eve can be expressed as

$$\mathbf{y}_E = \mathbf{H}_p^H(\theta_E) \mathbf{W} \mathbf{s}_{mpl} + \mathbf{n}_E. \tag{11}$$

Due to the miss of $\mathbf{H}_B$ and $\mathcal{A}$, the ML detection of Eve can only be conducted as

$$(\hat{m}, \hat{p}) = \underset{m,p}{\arg\min} \left\| \mathbf{y}_E - \begin{bmatrix} \cos\gamma_p b_m \\ \sin\gamma_p e^{j\eta_p} b_m \end{bmatrix} \right\|_2^2. \tag{12}$$

According to (12), Eve cannot detect the receiver index l resulting from the distributed cooperation in the proposed PSDM scheme. Furthermore, even when Eve gets the steering vector $\mathbf{H}_B$ and index l, it is still hard to conduct a perfect ML detector owing to the scrambling factor set $\mathcal{A}$, which imposes a serious phase rotation to the PM symbols.

Low-complexity near-ML detection at Bob. For alleviating the computational complexity in (10), a low-complexity near-ML (NML) detection is employed for the signal detection at Bob, which only requires $M + P + N_r$ Frobenius norm operations. First, the receiver index $\hat{l}$ is obtained by searching the maximum receive signal power, formulated as

$$\hat{l} = \underset{l}{\arg\min} \left\| |\mathbf{y}_{\mathrm{B}}| - \mathbf{e}_l \otimes \begin{bmatrix} 1 \\ 1 \end{bmatrix} \right\|_2^2. \tag{13}$$

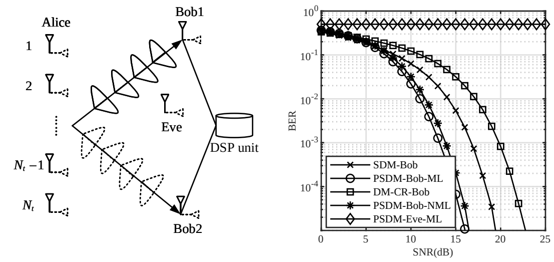
Then, the XPD parameter χ is required to be estimated and equalized to eliminate the XPD effect. Furthermore, the NML detection can be further implemented to obtain the polarization state symbol $\mathbf{p}_S(\gamma_{\mathrm{B}_{\hat{l}}}, \eta_{\mathrm{B}_{\hat{l}}})$ as

$$\hat{p} = \underset{p}{\arg\min} \left\| \mathbf{p}_S(\gamma_{\mathrm{B}_{\hat{l}}}, \eta_{\mathrm{B}_{\hat{l}}}) - \mathbf{p}_S(\gamma_p, \eta_p) \right\|_2^2. \tag{14}$$

Finally, the APM symbol can be detected as

$$\hat{m} = \underset{m}{\arg\min} \left| \frac{\tilde{y}_{B_{\hat{l}}}^h \alpha_{\hat{l}}^\dagger}{2\cos\gamma_{\hat{p}}} + \frac{\tilde{y}_{B_{\hat{l}}}^v e^{-j\eta_{\hat{p}}}}{2\sin\gamma_{\hat{p}}} - b_m \right|^2, \tag{15}$$

where $\tilde{y}_{B_{\hat{l}}}^h$ and $\tilde{y}_{B_{\hat{l}}}^v$ are the outputs of XPD equalization.



(a) (b)

Figure 1 (a). System model of PSDM; (b).BER performance comparison between DM-CR, SDM, and PSDM.

Conclusion and simulation results. In this contribution, the PM scheme has been employed in SDM systems with a polarization sensitive crossed-dipole array in the context of free-space transmission. Specifically, the steering vector of the polarization sensitive crossed-dipole array was introduced with the consideration of XPD, followed by a design of the transceiver structure. Finally, simulation results in Figure 1(b) demonstrate the bit errro rate (BER) performance comparison between PSDM, SDM, and DM-CR, where the number of bits per symbol is set to be 5 for all three schemes for fairness. As expected, the proposed PSDM system outperforms its counterparts in terms of both security and transmission performance.

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References

1 Y Xiao, W Tang, Y Xiao, et al. Directional modulation with cooperative receivers. IEEE Access, 2018, 6: 34992–35000
2 Q D You, Y P Xiao. Spatial and directional modulation with scrambling. Phys Commun, 2019, 100694.1-100694.8
3 S Benedetto, P Poggiolini. Theory of polarization shift keying modulation. IEEE Trans Commun, 1992, 40: 708–721
4 P Henarejos, A I Prez-Neira. Dual polarized modulation and reception for next generation mobile satellite communications. IEEE Trans Commun, 2015, 63: 3803–3812
5 S Dhanasekaran. Space-polarization shift keying modulation for MIMO channels. Wireless Pers Commun, 2016, 86: 1509–1539
6 P Arapoglou, P Burzigotti, M Bertinelli, et al. To MIMO or not to MIMO in mobile satellite broadcasting systems. IEEE Trans Wireless Commun, 2011, 10: 2807–2811
7 C Oestges, B Clerckx, M. Guillaud, et al. Dual-polarized wireless communications: From propagation models to system performance evaluation. IEEE Trans Wireless Commun, 2008, 7: 4019–4031