A Polarization State Modulation Based Physical Layer Security Scheme for Wireless Communications

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***Abstract*— A Polarization state Modulation based Physical Layer Security (PM-PLS) scheme is proposed to enhance the physical layer security of the wireless communication system. Such scheme uses the normal communication signal as the carrier, and conceals the confidential information in the carrier's polarization state. Moreover, utilizing the polarized channel differentia, the eavesdropper's channel quality can be severely worsened. Therefore, through PM-PLS scheme, both anti-detection and modulation information protection can be achieved. Furthermore, based on the proposed polarization constellation structure and polarization constellation encryption method, the depolarization effect caused impact to the desired receiver and eavesdropper are respectively analyzed. Finally, the simulations and experiments based on GNU Radio software platform are carried out to verify the security and efficiency of the proposed PM-PLS scheme.**

I. Introduction

Currently, the wireless communication's security mainly rely on the cryptographic techniques in the link and application layer; as for the physical layer, there is no protection. However, due to the wireless channel's openness, the unprotected physical layer can be a great security vulnerabilities to the eavesdropping [1].

To address this issue, the researches on physical layer security are carried out. Such researches can be classified into two categories. One category is preventing the eavesdropper to detect the target communication signal, such as the spread spectrum transmission techniques [2], frequency hopping techniques [3], beam-forming [1] and meteor burst communication techniques [4]. Through these anti-detection techniques, it will be hard for the eavesdropper to capture or interfere the target signal. But most of these security techniques can not guarantee the modulation information security once the transmitted signal is captured [5][6]; additionally, these techniques' security performance is at a price of low spectrum efficiency or high cost [6]. The other category is preventing the eavesdropper to decode modulation information from the captured signal. The related researches are mainly on the channel security capacity [7] and the security enhancement designs in physical layer [8]. The formers focus on information theory, and point out that the communication security can be realized if the legitimate user's channel is stronger than the eavesdropper's. The letters aim to deteriorate the eavesdropper's channel quality. For instance, through adopting the random constellation rotation or secured constellation mapping rule at the legitimate transmitter, the eavesdropper's channel quality can be deteriorated [8]. Likewise, utilizing the unique space differentia of the legitimate channel, the methods including antenna array transmission, directional modulation or artificial noise insertion also can worsen the eavesdropper's channel quality [8]. Through the above security enhancement methods, the target signal's modulation information can be protected. However, in the case of the interference attack, these methods will be helpless [6]. Thus, to ensure the physical layer security, the physical layer security methods should combine anti-detection and modulation information protection. Additionally, the efficiency and application cost should not be overlooked as well.

In this paper, a Polarization state Modulation based Physical Layer Security (PM-PLS) scheme is proposed. Firstly, PM-PLS scheme utilize the normal communication signal (hereinafter referred to as host signal) as the carrier; through modulating such carrier's polarization state, the scheme can conceal information in the host signal and realize the secure transmission; moreover, the host signal's communication quality does not suffer any impact. Thus, the anti-detection can be achieved. Secondly, through introducing the polarization state modulation, the polarized channel differentia can be exploited to increase the discrimination between the legitimate user's channel and the eavesdropper's. Due to the polarized channel differentia, the desired receiver and eavesdropper suffer different depolarization effect, including polarization dependent attenuation, channel dependent constellation rotation and channel dependent constellation distortion. So it will be hard for the eavesdropper to estimate modulation information from the captured signal, but as for the legitimate user, the communication quality can be guaranteed through utilizing the

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shared channel information. Therefore, the modulation information protection can be achieved. Additionally, a polarization constellation structure and constellation encryption method are also proposed for the PM-PLS scheme. Lastly, it should be noted that the proposed PM-PLS scheme can be conveniently performed on the basis of the traditional transceiver.

The remainder of this paper is as follows. In section II, the system model is depicted. In section III, the PM-PLS scheme is presented. Simulations and analysis are given in section IV. Finally, conclusions are drawn in section V.

II. The secure communication system model

The secure communication system model is depicted in Fig. 1. Let us consider three users, Alice, Bob and Eve, and three wireless MIMO channels, $\boldsymbol{H}_{AB}$, $\boldsymbol{H}_{AE}$ and $\boldsymbol{H}_{BE}$. Alice and Bob are legitimate users, and Eve is the eavesdropper. The confidential messages between Alice and Bob are transmitted through $\boldsymbol{H}_{AB}$, the Time-Division Duplex (TDD) method is adopted. According to the channel reciprocity in TDD system, $\boldsymbol{H}_{AB}$ can be acquired by Alice and Bob. Through channel $\boldsymbol{H}_{AE}$ and $\boldsymbol{H}_{BE}$, the wireless signal transmitted by Alice and Bob can be received by Eve, but the channel information $\boldsymbol{H}_{AE}$ and $\boldsymbol{H}_{BE}$ are unknown to Ave. Likewise, such channel information is also unknown to Alice and Bob.

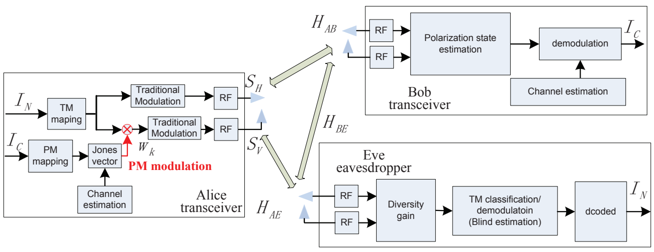

Fig. 1: The secure communication system model

When Alice sends confidential messages I_C to Bob, Alice will firstly generate a traditionally modulated (TM, including FM, FSK and PSK) host signal, such signal carry unclassified information I_T; then utilizing PM, the polarization state of the host signal is modulated to bear the confidential messages I_C. The concrete process is as shown in Fig. 1.

Firstly, unclassified information I_N is mapped to a group of TM constellation points for traditional modulation, the mapped constellation points are denoted as $\{C_k\}_{k=1}^{K}$; confidential information I_C is mapped to a group of polarization constellation points for polarization state modulation, the polarization constellation points are denoted as $\{D_k\}_{k=1}^{K}$. Then each TM constellation point C_k is duplicated; based on polarization decomposition, each D_k is exclusively mapped to a normalized Jones vector as (1) [9]. After that, each duplicated C_k is multiplied by w_k in the equation (1). Finally, each C_k and its duplication are processed by traditional modulation, digital to analog converter , up conversion and respectively transmitted by a pair of horizontal and vertical polarized antennas. The signals transmitted by each antenna can be expressed as (2) and (3)

$$D_k \xrightarrow{\text{Mapping}} \begin{bmatrix} 1 \\ w_k \end{bmatrix} = \begin{bmatrix} 1 \\ \tan\delta_k e^{j\phi_k} \end{bmatrix} \tag{1}$$

$$S_{\mathrm{H}} = E_k e^{[j2\pi f_c t + \phi_0(k)]} \tag{2}$$

$$S_{\mathrm{V}} = \tan\delta_k E_k e^{[j2\pi f_c t + j\phi_k + \phi_0(k)]} \tag{3}$$

where $\delta_k \in [0, \pi/2)$ and $\phi_k \in [0, 2\pi)$, E_k and $\phi_0(k)$ are the traditional modulation signal's amplitude and phase. For convenience, we define the radio of two signals' amplitude as the amplitude radio, and the difference between two signals' phase as the phase difference. It can calculated from (2) and (3) that the amplitude radio and phase difference of S_{H} and S_{V} are respectively $\tan\delta_k$ and ϕ_k. According to [9],S_{H} and S_{V} will be combined as $\vec{P}_k$ polarized electromagnetic wave in the far field, and such polarization state carries transmitting information I_C. In addition, the carrier's amplitude E_k and phase $\phi_0(k)$ still bear information I_N. From the above illustration, we also can find that the entire polarization modulation branch is achieved through the baseband digital signal processing, which means the polarizations state modulation can conveniently be performed on traditional transceiver.

In the far field, Bob utilizes a pair of horizontal and vertical polarized antennas to perform PM demodulation. As shown in Fig. 1, firstly, the arrived polarization state is estimated by calculating the normalized Jones vector from the received signals [10]. Then, the transmitted polarization constellation point D_k is decided through utilizing the channel information and the Maximum Likelihood (ML) decision rule [10]. Finally, I_C is recovered according to the constellation reverse mapping. In addition, the TM demodulation also can be performed from the received signals. During the polarization state modulation, it can be found that the host communication signal's amplitude and phase is changed when multiplying w_k. But such change will not result in interference to the host communication through designing proper polarization constellation. Such design will be illustrated in the next section.

III. The PM-PLS scheme

A. The anti-detection design

In this subsection, the anti-detection design of PM-PLS scheme is illustrated. To ensure anti-detection, the host communication quality should not be affected; and the change to the host communication signal should not be detected by the current signal detection methods.

To avoid the interference to host communication, a secure polarization state constellation design is illustrated. As the illustration in above section, PM will introduce amplitude attenuation and phase rotation to the host signal when multiplying w_k, such attenuation and rotation is dependent on the transmitted polarization state constellation point D_k. The relation between w_k and D_k can be described through Fig. 2.

According to [9], each polarization state can be mapped to an exclusive point on the surface of the Poincare sphere. Poincare sphere is a graphical tool for visualizing different types of polarization states, each point on the sphere surface represents a difference polarization state, the detailed

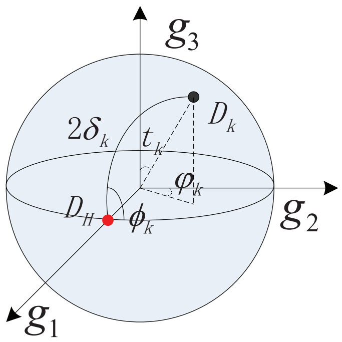

Fig. 2: The polarization state constellation point on the unit Poincare sphere

introduction can be found in [9]; As shown in Fig. 2, D_k is the transmitted polarization constellation point, which is mapped to polarization state $\vec{P}_k$; D_{H} denotes the polarization constellation point corresponding to horizontal polarization state $\vec{P}_{\mathrm{H}}$. $2\delta_k$ is the length of the arc from D_k to D_{H}, ϕ_k is the angle between such arc and the equator; t_k and φ_k are the D_k's co-latitude and azimuth on this Poincare sphere. Thus, the introduced amplitude attenuation and phase rotation can be controlled through selecting proper polarization constellation points. For FSK and PSK modulated host signal, the constellations should have equal ϕ_k, which means the designed polarization constellation is distributed on the half circle passing through D_{H}. As shown in Fig. 3, there are infinite half circles passing through D_{H}. For convenience, we define each half circle as the constellation arc. Selecting the points on the same constellation arc, the introduced phase rotation is a fixed value, and such rotation will be corrected through normal channel estimation and equalization. Therefore, the host communication quality is not affected. Additionally, the horizontal and vertical polarized branches can offer diversity gain to the host receiver and improve the host communication quality.

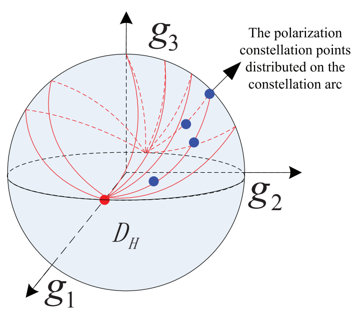

Fig. 3: The constellation arcs and the polarization constellation points

Spectral characteristic is an important criterion to search and identify the target communication signal, such as central frequency, bandwidth and spectral shape, etc [2]. Thus, to avoid be detected, the change of the host signal's spectral characteristic should be unrecognized after performing PM. Through the above secure polarization constellations, such target can be ensured. As shown in Fig. 3, the designed constellation points have same ϕ_k. Adopting such constellation, the transition of the transmitted polarization states is continuous; and the produced Power Spectral Density (PSD) has narrower main lobe and larger side lobe attenuation , compared with the traditional modulation method with the same modulation order and symbol rate [11]. Therefor, the change to the host signal's spectral characteristic caused by PM is inconspicuous.

B. The modulation information protection design

To prevent the eavesdropper acquiring the PM's modulation information from the captured signal, a constellation encryption method is proposed. Such method is consist of two preventive measures. One is utilizing the depolarization effect to worsen the eavesdropper's channel quality; the other is selecting a different constellation arc to produce the constellation points during each channel estimation period, such channel estimation period is defined as the period between two adjacent channel estimation.

Considering a 2×2 polarimetric multi-tap fading channel, the transfer function during each channel estimation period can be expressed as [12]

$$\boldsymbol{H}=\begin{bmatrix} \sum_{r=1}^{R_{\mathrm{H}}} h_r^{\mathrm{HH}} e^{j2\pi f_n \tau_r^{\mathrm{H}}} & \sum_{r=1}^{R_{\mathrm{V}}} h_r^{\mathrm{VH}} e^{j2\pi f_n \tau_r^{\mathrm{V}}} \\ \sum_{r=1}^{R_{\mathrm{H}}} h_r^{\mathrm{HV}} e^{j2\pi f_n \tau_r^{\mathrm{H}}} & \sum_{r=1}^{R_{\mathrm{V}}} h_r^{\mathrm{VV}} e^{j2\pi f_n \tau_r^{\mathrm{V}}} \end{bmatrix} \quad (4)$$

where R_{H} and R_{V} respectively denote the number of the multi-paths associated with the H-polarized and V-polarized signal component; τ_r^X is the propagation delay associated with the r_{th} propagation path for the X-polarized component; h_r^{XY} represents a complex channel gain between the transmitted X-polarized component and the received Y-polarized component for the r_{th} propagation path.

Since Bob and Alice can completely acquire the channel transfer function $\boldsymbol{H}_{AB}$, utilizing such function, Bob can encrypt the polarization constellation points through multiplying C_P

$$\tilde{D}_k = D_k C_P \quad (5)$$

where k is the integer in the range of $[1, M_p]$, M_p is PM's modulation order; C_P can be expressed as

$$\boldsymbol{C_P} = \boldsymbol{V}_{AB}^{+} \begin{bmatrix} \frac{\sqrt{\lambda_{AB,2}}}{\sqrt{\lambda_{AB,2}\cos^2\delta_i + \lambda_{AB,1}\sin^2\delta_i}} & 0 \\ 0 & \frac{\sqrt{\lambda_{AB,1}}}{\sqrt{\lambda_{AB,2}\cos^2\delta_i + \lambda_{AB,2}\sin^2\delta_i}} \end{bmatrix} \boldsymbol{U}_{AB}^{+} \quad (6)$$

where $\boldsymbol{U}_{AB}$ and $\boldsymbol{V}_{AB}$ are the unitary matrixes by the singular value decomposition of $\boldsymbol{H}_{AB}$ [9], such decomposition can be expressed as (7); $(\cdot)^+$ denotes Hermitian operation; $\lambda_{AB,1}$ and $\lambda_{AB,2}$ ($\lambda_{AB,1} \geq \lambda_{AB,2} \geq 0$) are the eigenvalues; The ratio of such two eigenvalues can be defined as the PDL value according to [13]

$$\boldsymbol{H}_{AB} = \boldsymbol{U}_{AB}\boldsymbol{\Sigma}_{AB}\boldsymbol{V}_{AB} = \boldsymbol{U}_{AB}\begin{bmatrix}\sqrt{\lambda_{AB,1}} & 0 \\ 0 & \sqrt{\lambda_{AB,2}}\end{bmatrix}\boldsymbol{V}_{AB} \quad (7)$$

$$PDL = 10\lg\left[\lambda_{AB,1}/\lambda_{AB,2}\right] \quad (8)$$

After encryption, the polarization constellation points received by Bob and Eve can be respectively expressed as

$$\tilde{D}_{Bob,k} = D_k C_P \boldsymbol{H}_{AB} + n \quad (9)$$

$$\tilde{D}_{Eve,k} = D_k C_P \boldsymbol{H}_{AE} + n \quad (10)$$

Where n denotes the Additive White Gaussian Noise (AWGN). If we substitute equation 6 into equation 9, equation 9 can be rewrote as

$$\tilde{D}_{Bob,k} = D_k \rho_{AB} + n \quad (11)$$

where ρ_{AB} is

$$\rho_{AB} = \frac{\sqrt{\lambda_{AB,2}\lambda_{AB,1}}}{\sqrt{\lambda_{AB,2}\cos^2\delta_i + \lambda_{AB,1}\sin^2\delta_i}} \quad (12)$$

Also, equation (10) can be rewrote as

$$\tilde{D}_{Eve,k} = D_k \boldsymbol{\Sigma}_{CP}\boldsymbol{U}_{AB}^{+}\boldsymbol{U}_{AE}\boldsymbol{\Sigma}_{AE}\boldsymbol{V}_{AE} + n \quad (13)$$

where $\boldsymbol{\Sigma}_{CP}$ is the diagonal matrix in euqation (6);$\boldsymbol{U}_{AE}$, $\boldsymbol{\Sigma}_{AE}$ and $\boldsymbol{V}_{AE}$ are matrixes produced by the singular value decomposition of $\boldsymbol{H}_{AE}$. $\boldsymbol{U}_{AE}$ and $\boldsymbol{V}_{AE}$ are unitary matrixes, $\boldsymbol{\Sigma}_{AE}$ is a dignal matrix as

$$\boldsymbol{\Sigma}_{AE} = \begin{bmatrix}\sqrt{\lambda_{AE,1}} & 0 \\ 0 & \sqrt{\lambda_{AE,2}}\end{bmatrix} \quad (14)$$

It can be found from (11) that the polarization constellation points received by Bob only undergo an attenuation. The bit error rate of the PM branch is derived as

$$P_{BER} = \Big[\int_{\pi-\theta_0}^{\pi}\int_{0}^{2\pi} f(t_i,\varphi_i)\mathrm{d}\varphi_i\mathrm{d}t_i + \int_{\theta_0}^{\pi-\theta_0}\int_{0}^{\alpha(\theta_0,t_i)} f(t_i,\varphi_i)\mathrm{d}\varphi_i\mathrm{d}t_i\Big]/log_2^{M_P} \quad (15)$$

where $i \in [1, M_P]$, and M_p is the PM modulation order; N_0 is the variance of the noise; P_T is the transmitting power; $\alpha(\theta_0, t_i)$ is as (16), and θ_0 is the half minimum distance of the adjacent polarization constellation points; $f(t_i, \varphi_i)$ is the joint probability density function of the received polarization state's co-latitude and azimuth as (17) [14]

$$\alpha(\theta_0, t_i) = \arccos(\tan\theta_0/\tan t_i) \quad (16)$$

$$f(t_i,\varphi_i) = \frac{1}{4\pi}\sin t_i\left(e^{-\rho_{AB}P_T\frac{1-\cos t_i}{2N_0}}\right)\left[1+\rho_{AB}P_T\frac{1+\cos t_i}{2N_0}\right] \quad (17)$$

The impact suffered by Eve's received constellation points is analyzed as follows.

According to equation (13), the matrixes multiplied by $\tilde{D}_{Eve,k}$ can be classified into two categories: unitary matrix and diagonal matrix. When multiplying unitary matrix, the polarization constellation points will be rotated as a rigid body on the Poincare sphere. Fox example, assuming D_i and D_j are two adjacent constellation points (as shown in Fig. 4), and their spherical distance is L_T. Such distance will keep invariable after undergoing the unitary matrix caused rotation, also the carried information is not lost. However, when multiplying diagonal matrix, the polarization constellation points will move along with the constellation arc. As shown in Fig. 5, the constellation points will move toward D_{H}, namely D_i and D_j are moved to D_v and D_u. Thus, it can be found that the diagonal matrix will result in the polarization constellation distortion, also the signal power is attenuated, and the carried information will be lost.

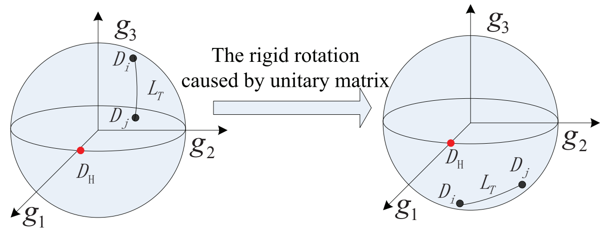

Fig. 4: The unit Poincare sphere

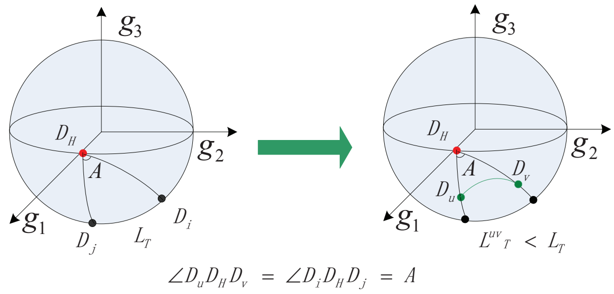

Fig. 5: The unit Poincare sphere

Based on the above analysis, we can find the polarization constellation received by Eve firstly suffers a rotation caused by $\boldsymbol{V}_{AB}^{+}$; then the rotated constellation is distorted caused by $\boldsymbol{\Sigma}_{CP}$, next the constellation is rotated again by $\boldsymbol{U}_{AB}^{+}$ and $\boldsymbol{U}_{AE}$, after that the rotated constellation suffers a further distortion caused by $\boldsymbol{\Sigma}_{AE}$, finally the severely distorted constellation is rotated thirdly by $\boldsymbol{V}_{AE}$. Thus, the polarization constellation received by Eve is severely distorted. Additionally, a different constellation arc is selected to produce the constellation points during each channel estimation period. Therefore, it is impossible for Eve to depict the recognizable polarization constellation structure and estimation the adopted constellation arc, namely the modulation information will not be eavesdropped by Eve.

IV. Simulations

In this section, the simulations based on MATLAB and experiments based on GNU Radio software platform are performed to evaluate PM-PLS scheme's anti-detection performance and modulation information protection performance.

A. The anti-detection performance verification and analysis

To examine the anti-detection performance, the affect to host signal's Power Spectral Density (PSD) after performing PM is analyzed, also the spectral similarity is measured; then the host communication's Bit Error Rate (BER) after performing PM is evaluated.

The TM methods adopted by host communication include MSK and PSK, the root raised cosine filter is used to generate the PM modulated signal and PSK modulated signal. For PM, the proposed polarization constellation in section III is adopted. Through MATLAB simulation tool, the PSD of MSK, PSK and PM are shown in Fig. 6

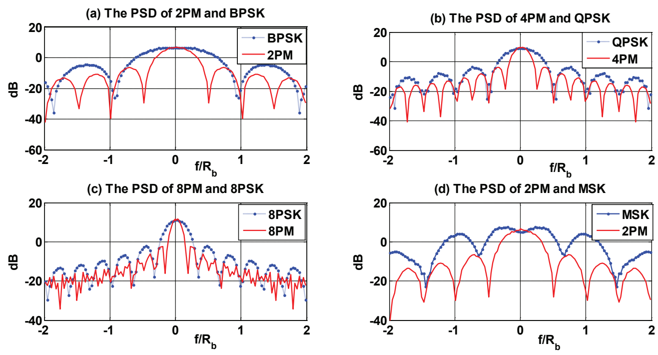

Fig. 6: The PSD of 2PM, BPSK, QPSK, 8PSK and MSK

It can be found from Fig. 6 that PM's main lobe is narrower, and also the side lobe attenuated more rapidly, compared with MPSK and MSK. For 2PM, 4PM and 8PM, the main lobes are respectively $0.49R_b$, $0.25R_b$ and $0.16R_b$, where R_b denotes the symbol rate. While for BPSK, QPSK, 8PSK and MSK, the main lobes are respectively $0.928R_b$, $0.51R_b$, $0.32R_b$ and $0.77R_b$. In addition, for 2PM, 4PM and 8PM, the attenuations at the first side lobs are $13dB$, $13.4dB$ and $14.44dB$; while for BPSK, QPSK, 8PSK and MSK, such attenuations are $11.2dB$, $12dB$, $12.9dB$ and $3.3dB$.

The spectral similarity between the host communication signal and the PM-PLS produced signal is measured. According to [15], the spectral similarity can be defined as

$$SCM(x,y) = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{N}(y_i - \bar{y})^2} \qquad (18)$$

Where $\bar{(\cdot)}$ denotes the average calculation, x and y are the compared spectrum data. Utilizing the GNU Radio software platform, the host communication signals adopting MSK and PSK are respectively produced, and the PM-PLS communication signals adopting MSK-PM PSK-PM are also respectively generated. Through spectrum analyzer, each communication signal is sampled, and then the corresponding spectrum data is calculated through fourier transform. The symbol rate of host communication is set as 1000ks/s. For PM-PLS scheme, the symbol rate of TM branch is also set as 1000ks/s; the symbol rate of PM branch is set as $1000/i$ ks/s, where $i = 1,2,4,8,16$. The root raised cosine filter is used to generate the PSK modulated host signal and PM-PLS modulated signal. The transmitting power is same for all the modulation methods. To reduce the impact from channel's random variation, 100 groups of data are sampled each time to calculated the average spectral similarity. The sample rate is set as 2MHz/s, the sample size is 20000. The calculated average spectral similarity between host communication signal and PM-PLS communication signal is shown in Fig. 7

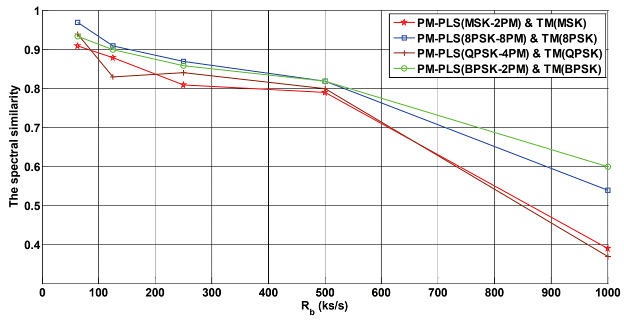

Fig. 7: The spectral similarity between TM modulated signal and PM-PLS modulated signal

From Fig.7, it can be found the similarity between TM modulated signal and PM-PSL modulated signal is continuously decreasing with the increasing symbol rate of the PM branch. When such symbol rate is blew half of the TM symbol rate, the similarity can stabilized at more than 80%. Therefore, in order to obtain better concealment performance, PM branch's symbol rate should be less than half of the TM branch's symbol rate.

Also, the BER of TM branch is analyzed when the symbol rate of PM branch varies from 62.5ks/s to 1000ks/s. The results are shown in Fig.8.

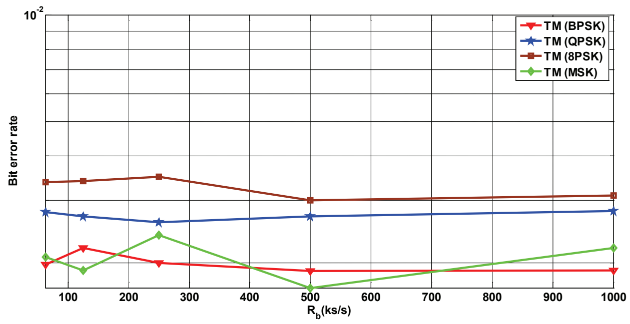

Fig. 8: The BER performance of the TM branch

From the figure, it can be found the BER curves of the TM branches are flat, even when the PM branch's symbol rate is 1000ks/s, the BER performance of each TM branch still does not degrade. Thus, it can be concluded that PM does not affect the host communication quality according to the above designs.

B. The modulation information protection performance verification and analysis

To verify the PM-PLS scheme's modulation information protection performance, the experiments based on GNU Radio platform are performed in a working area of the institute of information engineering, the layout of which is depicted in Fig. 9. In the experiment, Alice uses the GNU Radio platform to generate the PM-PLS communication signal, the GNU Radio platform is equipped with a Universal Software Radio Peripheral X300 (USRP X300) hardware and a pair of orthogonal polarized antennas. Likewise, the same GNU platforms are adopted by Bob and Eve. Bob uses such platform to receive and demodulate the PM-PLS communication signal; while Eve try to estimate the modulation information of the PM branch transmitted by Alice. If the polarization constellation structure can be correctly depicted by Eve, it can be assumed that the modulation information is successfully eavesdropped, therefore the PM Modulation Classification Rate (MCR) is used to evaluate the modulation information protection performance. In addition, the confidential information carried by the polarization state also should be accurately demodulated by Bob, thus the Bit Error Rate (BER) of the demodulated information is evaluated. Through channel estimation, the channel information is shared between Alice and Bob, and the channel pre-compensation and equalization are adopted. For Eve, the channel blind equalization based on constant modulus algorithm is adopted to improve the classification capability. In order to verify impact caused by the channel depolarization effect, the locations of Alice, Bob and Eve are changed to diversify the channel condition, such locations are denoted as $\{\text{Site}Xi \mid X \in [\text{A(Alice), B(Bob), E(Eve)}]; i \in [1,5]\}$. Also, the distance between Bob and Eve is far enough to ensure the channel differentia. The transmitting power of USRP X300 is controlled through adjusting a power factor, such factor is in the range of $[0,1]$, so the RSNR also can be controlled through changing the power factor. The related parameters in this experiment are shown in table I. To get steady BER and MCR estimation, we made 100 times experiment with each transmitting power and location, then calculated the average BER and MCR. The experimental results are shown in Fig. 10, Fig. 11, Fig. 12, and Fig. 13.

The curves in Fig. 10 show the BER performance of the TM branch and PM branch with the varying RSNR. During the experiment, the locations of Alice and Bob are fixed, so the channel fluctuation can be considered as flat, the measured PDL degree is the range of $[10dB, 13dB]$. From the curves, we can find the BER performance of PM and TM(MPSK) continually improves with the increasing RSNR, but when RSNR is upgraded to more than $22dB$, all the curves begin to rise, this is because the amplifier of the transmitter is operating in the nonlinear region, the produced nonlinear distortion deteriorates the BER performance of PM and TM(MPSK). Compared with the PSK, PM's BER performance is better when RSNR is in the range of $[16dB, 20dB]$, and the superiority is more obvious in the case of 2PM and 4PM.

The curves in Fig. 11 show the BER performance of the TM branch and PM branch with the varying PDL degree. During the experiment, the RSNR is stabled at 15dB, the locations of Alice, Bob and Eve are changed to realize different depolarization effect, the measured PDL degree is in the range of $[10dB, 20dB]$. From the curves, we can find the BER performance of MPM and TM(MPSK) continually degrades with the increasing PDL degree. Compared with PSK, the curves of MPM rise more rapidly, which means PM suffer more impairment from the PDL effect. Compared with BPSK, the superiority of the 2PM's BER performance is

TABLE I: The related parameters of the experiments based on GNU Radio platform

the transmitted carrier frequency	2.424 GHz
the modulation method of TM branch	M-PSK
the symbol rate of TM branch	1000ks/s
the symbol rate of PM branch	1000ks/s
the transmitted data size	10 Mbits
the environment PDL degree	10 dB $\sim$ 20 dB
the channel estimation interval	0.5 ms
the Receiving Signal to Noise Ratio (RSNR)	10dB $\sim$ 28dB
the XPD between the dual polarized antennas	28 dB
the mounting height of the antennas above the floor	2 m

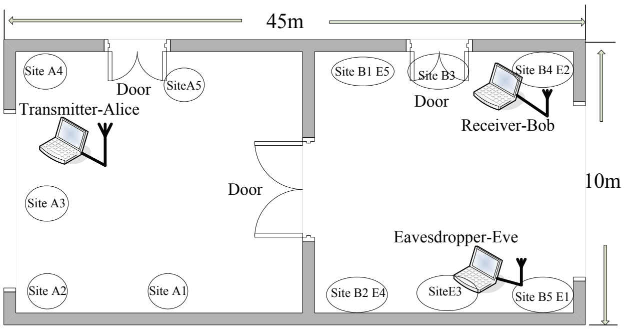

Fig. 9: The layout of the working area

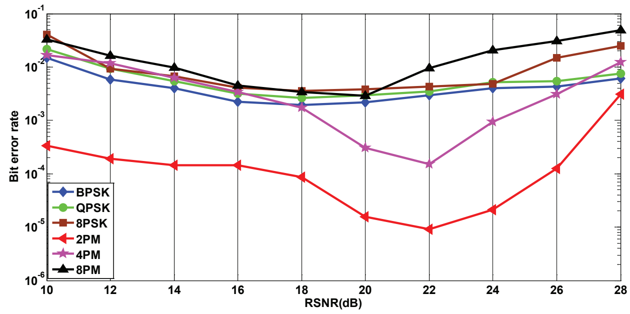

Fig. 10: The BER of PM and TM(MPSK) with the varying transmitting power

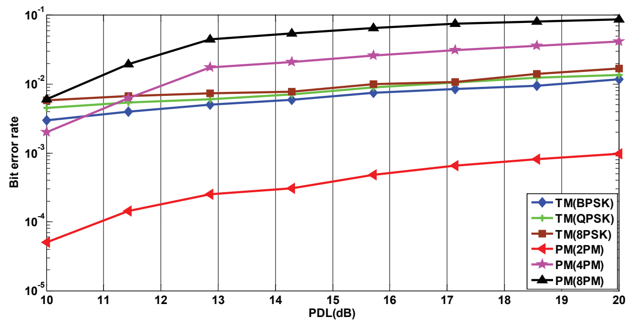

Fig. 11: The BER of PM and TM(MPSK) with the varying PDL degree

obvious, while compared with QPSK, the BER performance of 4PM is better when PDL degree is blew 10dB.

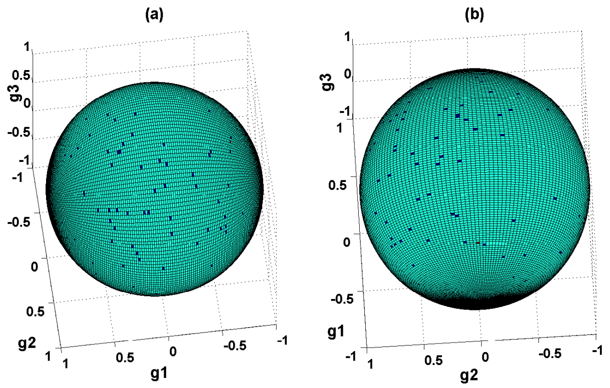

Fig. 12: The polarization constellation points received by Eve; (a) is the front view; (b) is the back view

When PM modulation order is 2, and the RSNR is stabled at 22dB, the polarization constellation points received by Eve are shown in Fig. 12. It can be found the received the polarization constellation points are randomly distributed on the poincare sphere. When the modulation order is greater or the RSNR is lower, the distribution of the received polarization constellation points is more random. Such randomness is resulted from two factors: one is the depolarization effect caused constellation rotation and distortion, the other is the variation of the constellation arc. Therefore, it can be considered that Eve can not acquire any modulation information. The experimental results also confirm such conclusion, the MCR realized by Eve is 0. Likewise, in the same experimental condition, the polarization constellation points received by Alice are also shown in Fig. 13. The transmitted constellation points are denoted as D_m and D_n (the red dots in Fig. 13), the received constellation points are denoted as blue dots. It can be found that the received constellation points are respectively converged to D_m and D_n.

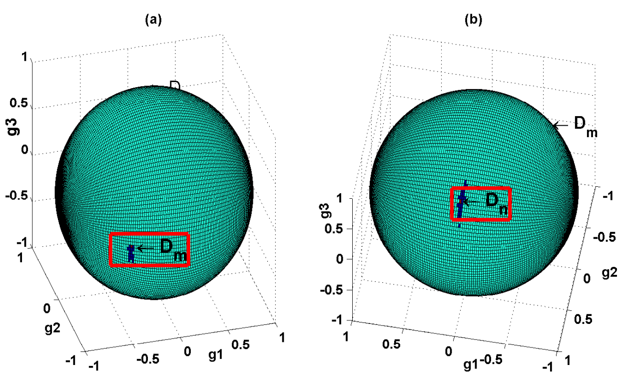

Fig. 13: The polarization constellation points received by Bob; (a) is the front view; (b) is the back view

V. Conclusions

In this paper, we have proposed a polarization modulation based physical layer secure scheme. Such scheme has the anti-detection performance and modulation information protection performance. Based on the traditional transceiver, the PM-PLS scheme including the polarization state modulation, polarization constellation, polarization state demodulation and polarization constellation encryption is designed. In addition, the experiments based on the GNU Radio software platform are carried out in an indoor scenario to verify the PM-PLS performance. The experimental results show that the PM-PLS scheme can effectively prevent the eavesdropper to detect or recognize the secure communication link, also the bit error rate performance of the PM-PLS scheme has superiority over the traditional PSK modulation method.

References

[1] A. Mukher jee, S. A. A. Fakoorian, J. Huang and A. L. Swindlehurst. "Principles of Physical Layer Security in Multiuser Wireless Networks: A Survey," *IEEE Communications Surveys AND Tutorials.*, Vol. 16(3), pp. 1550-1573, 2015.

[2] Q. Z. Ahmed, K. H. Park and M. S. Alouini. "Ultrawide Bandwidth Receiver Based on a Multivariate Generalized Gaussian Distribution," *IEEE Transactions on Wireless Communications.*, Vol. 14(4), pp. 1800-1810, 2015.

[3] L. Zhao, L. Wang, G. Bi, L. Zhang and H. Zhang. "Robust Frequency-Hopping Spectrum Estimation Based on Sparse Bayesian Method," *IEEE Transactions on Wireless Communications.*, Vol. 14(2), pp. 781-793, 2015.

[4] Z. Li, X. Chen, Y. Li, N. C. Beaulieu, and M. S. Obaidat. "An Adaptive Algorithm for Joint Data Detection and Channel Estimation for Meteor Burst Communications Based on Per-Survivor Processing," *2015 IEEE Global Communications Conference (GLOBECOM).*, pp. 1-6, 2015.

[5] T. Fusco, L. Izzo, A. Napolitano and M. Tanda. "On the second-order cyclostationarity properties of long-code DS-SS signals," *IEEE Transactions on Communications.*, Vol 54(10), pp. 1741-1746, 2006.

[6] W. Trappe. "The challenges facing physical layer security," *IEEE Communications Magazine.*, Vol. 53(6), pp. 16-20, 2015.

[7] X. Guan, Y. Cai and W. Yang. "On the Reliability-Security Tradeoff and Secrecy Throughput in Cooperative ARQ," *IEEE Communications Letters.*, Vol. 18(3), pp. 479-482, 2014.

[8] H. M. Wang and X. G. Xia. "Enhancing wireless secrecy via cooperation: signal design and optimization," *IEEE Communications Magazine.*, Vol. 53(12), pp. 47-53, 2015.

[9] Zhaowen Zhuang, Shunping Xiao and Xuesong Wang. "Radar polarization information processing and application," *National Defense Industry Press.*, Beijing, 1999.

[10] Dong Wei, Chunyan Feng, Caili Guo and Liu Fangfang. "A Power Amplifier Energy Efficient Polarization Modulation Scheme Based on the Optimal Pre-Compensation," *Communications Letters, IEEE .*, Vol 17(3), pp. 513-516, 2013.

[11] S. Benedetto and P. Poggiolini. "Highly bandwidth efficient transmission through continuous polarisation modulation," *Electronics Letters.*, Vol 26(17), pp. 1392-1394, 1990.

[12] IST-4-027756 WINNER II D1.1.1 *WINNER II interim channel models,* 1.0, December 2006.

[13] T. Pratt, B. Walkenhorst and S. Nguyen. "Adaptive polarization transmission of OFDM signals in channels with polarization model depersion and polarization-dependent loss," *IEEE Trans. WIRELESS COMMUNICATION.*, Vol, 8(4), pp.3354-3359, 2009.

[14] Benedetto S. and Poggiolini P. T.,"Multilevel polarization shift keying: optimum receiver strunciture and performance evaluation," *IEEE Trans. Communication.*, Vol. 42. pp.1174-1186, 1994.

[15] B. Chen, A. Vodacek and N. D. Cahill. "A Novel Adaptive Scheme for Evaluating Spectral Similarity in High-Resolution Urban Scenes," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing.*, Vol, 6(3), pp.1376-1385, 2013.