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Multi-Envelop Polarization Shift Keying Modulation for Digital Optical Communications

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Abstract

In this paper, a multi-envelop polarization shift keying (POLSK) modulation scheme for digital optical communications is proposed newly. Two multi-envelop 16-ary constellation structures are showed and applied to the digital optical communication systems. In this transmission scheme, a multiple state of polarization (SOP) is used as the carrier of information. The performance of bit error rate (BER) of the proposed systems are also computed and analyzed in the additive white Gaussian noise (AWGN) environment. Two kinds of receivers, containing the conventional coherent detection (CD) based on Stokes parameters and the direct detection (DD) using maximum likelihood (ML) rule, are exploited to demodulate the polarized optical signals. The theoretical values and experimental values are compared. Computer simulation results indicate that the experimental results of the proposed system are very similar to the theoretical values. And the system performance using DD receiver is better than the CD receiver for the multi-envelop POLSK modulation scheme if a special constellation structure is adopted.

Keywords: multi-envelop constellation, polarization shift keying, digital optical communications, bit error rate.

1. INTRODUCTION

Polarization shift keying (POLSK) is a technique that exploits the state of polarization (SOP) of a fully polarized lightwave as the information bearing parameter to modulate the transmitted optical signals [1]. A great deal of investigations about the modulation methods and the performance analysis have been published in the past two decades [2][8]. In the recently years, the optical technique have also been applied to the orthogonal frequency division multiplexing (OFDM) system [9]. But the constellation structure we have used is still restricted in the two dimensional (2-D) space or a single-envelop three dimensional (3-D) spaces [10].

In his paper, a multi-envelop SOP constellation points are located on two different spheres, and propagated in double mode fiber. In principles of optics, a SOP is fully described by the Stokes parameters [11]. The character of the polarization lightwave in the electromagnetic field can be completely defined by the amplitudes of two components and their phase difference. In the previous researches, the SOP points with the same power density are distributed on a spherical surface which called ‘’poincare sphere”. For the multi-envelop constellations we proposed, we name “inner poincare sphere” and “outer poincare sphere” shown in Fig.1 (a) and (b) have been emerged in [1][4][10]. We proposed two different 16-ary constellations structure, having cube-in-cube constellation structure and the multiple symmetry tetrahedron constellation structure. In these two constellations, all of the signals have two different optical intensities. So they must be propagated through the double mode fiber. A simple performance analysis with regard to the bit error rate (BER) and the computer simulation results are given in this paper. In the receiver, we detect the received signal using the coherent detection (CD) and regenerate the original signal transmitted by the Stokes parameters. In addition, a direct detection (DD) technique by the maximum likelihood (ML) rule is also exploited. Simulation results demonstrate that the performance of DD is better than the CD demodulation course. Especially, the advantage of the DD is more obvious in the case of the second kind of 16-POLSK modulation.

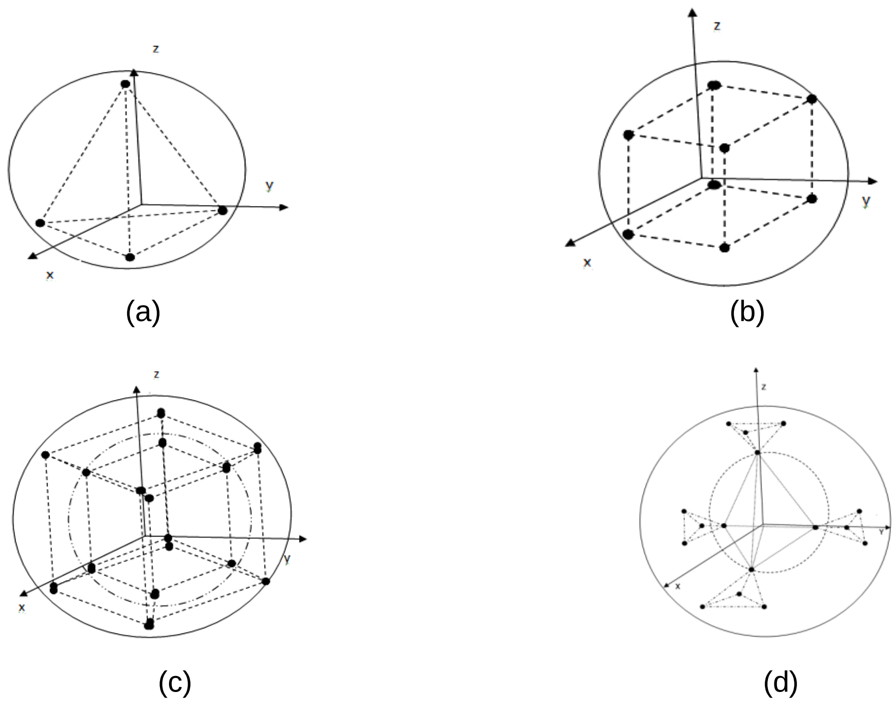

Fig.1. The 3-D signal constellations for POLSK modulation scheme. (a) 4-POLSK (b) 8-POLSK (c) 16-POLSK, first kind and (d) 16-POLSK, second kind.

2. POLARIZATION MODULATION

In this section we firstly give a simple review with respect to the theory of POLSK modulation. At the same time, a system diagram which is simplified is also applied and analyzed.

A.Theory : In the electromagnetic field, the SOP of a fully polarized lightwave can be conveniently described through the Stokes parameters. Give a reference plane (x, y) normal to the direction of propagation axis z, the expression of plane wave can be written as-

$$E = E_x x + E_y y$$
$$E_x = a_x e^{j(\omega t + \phi_x)} \qquad (1)$$
$$E_y = a_y e^{j(\omega t + \phi_y)}$$

Then the four Stokes parameters, in the general form, are computed as follow-

$$S_0 = a_x^2 + a_y^2$$
$$S_1 = a_x^2 - a_y^2$$
$$S_2 = 2 a_x a_y \cos\delta \qquad (2)$$
$$S_3 = 2 a_x a_y \cos\delta$$

where the phase difference is $\delta = \phi_x - \phi_y$ (3)

According to the above equations, the SOP is completely determined by the amplitude of the components a_x and a_y and their phase difference δ. In (2) the parameters depended on time have been omitted for notational simplicity. The Stokes parameter S_0 represents the optical intensity of a SOP point in the propagation direction z. The following equation also holds-

$$S_0^2 = S_1^2 + S_2^2 + S_3^3 \qquad (4)$$

Apparently, the S_i can be represented in a three dimensional space with unit vectors $\hat{s}_1, \hat{s}_2, \hat{s}_3$. This space is called as "Stokes space". A geometric representation of the SOP on the surface of called "Poincare sphere" is shown in Fig.2. S_0 is equivalent to

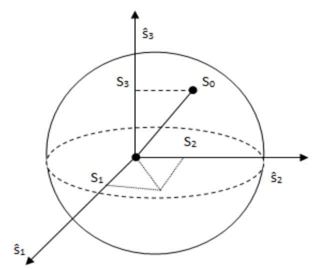

Fig.2. Representation of the polarization state on the poincare sphere.

the radius of sphere. In the previous literature, the optical signal is only propagated in single mode fiber channel owing to all the transmitted signal have the same optical intensity. In this paper, two kinds of new constellations which are the cube-in-cube constellation structure and the multiple symmetry tetrahedron 16-ary constellation structure are proposed. All the SOP signals can be considered distributing on the two different "Poincare sphere". In the case of Fig.1(c), only one distinction is that a "outer poincare sphere" is extended relative to the original "inner poincare sphere". It just is an extension of light intensity in the transmitter. For the second kind 16-aray constellation structure, the variable of the phase difference factor is more complex. Unlike the conventional POLSK modulation scheme, two different optical intensity signals must be generated in the transmitter and propagated in the double mode fiber channel.

B. *POLSK system*: A simple POLSK system block diagram is designed and drawn in Fig.3. In the Fig.3, the Jones vector [12] is exploited. For a fixed polarization state, the Jones vector can write as-

$$E_j = \begin{pmatrix} E_x \\ E_y e^{j\phi} \end{pmatrix} \qquad (5)$$

the phase of the component E_x is set to zero. So, we only use the phase difference to represent the phase of component of E_y. This way is very helpful to reduce the complexity of system. Two

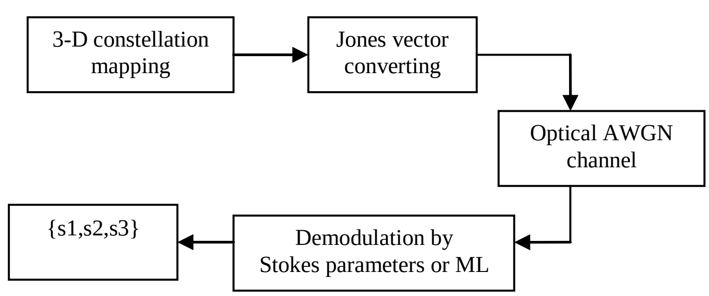

Fig. 3.A A block diagram of POLSK system.

kinds of demodulation methods are utilized. First one is to demodulate the original signal according to the Stokes parameters. The receiver split firstly the two components E_x and E_y by the polarization beam splitter and demodulate the phase difference by E_y. And the original Stokes parameters can be obtained using equation (2). The second one is to take advantage of sthe ML rule to demodulate the original Stokes parameters directly.

Considering the programming environment, we assume that the SOP is distributed by additive white Gaussian noise (AWGN) in the fiber channel. In addition, we have omitted the phase noise. It is reasonable if we make some hypotheses that are verified in [1].

3. PERFORMANCE

We start this section from the relative theoretical value. And some simulation results for the POLSK system which has been simplified are given. The comparison between the theoretical value and the experimental value will be carried out and discussed. The performances of rough upper boundary of bit error probability in the case of 4 and 8 POLSK systems have been analyzed in [1]. The expressions as follow-

$$P_{ub}\left(E\right)_{4-POLSK} = \left(0.7882\right)e^{\frac{A^2}{4\sigma^2}(0.4226)} \qquad (6)$$

and $$P_{ub}\left(E\right)_{8-POLSK} = \left(0.9082\right)e^{\frac{A^2}{4\sigma^2}(0.1835)} \qquad (7)$$

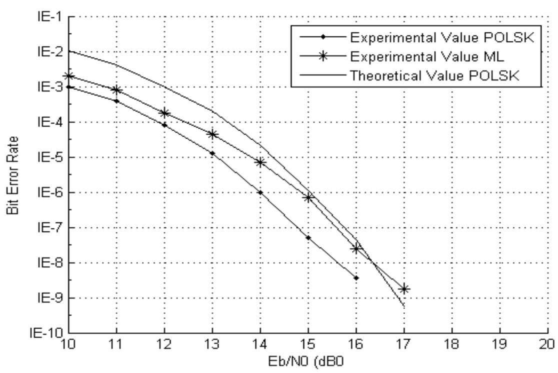

Fig.4. Bit error rates for 4-ary constellation.

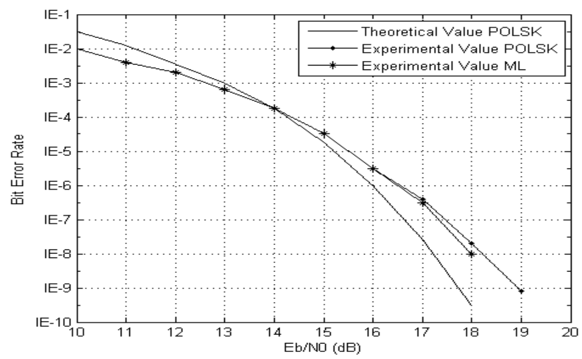

Fig.5. Bit error rates for 8-aray constellation

Where A^2 represents the power of one symbol in the POLSK constellation, σ is the standard variance of AWGN channel. The bit error probability curves are reported in Fig. 4 and 5 versus $\gamma = E_b/N_0$, the ratio between the energy per bit and noise spectral density. Observing these two figures, we can get conclusion that the experimental value is located below the theoretical value when γ is not larger than 15 dB, and the ML demodulation scheme can get better performance than the Stokes parameters demodulation scheme. The gain can reach around 0.8 dB in the case of 4-ary POLSK system. In the Fig.5 the curves are almost same of this two demodulation courses.

For the 16 POLSK constellation modulation scheme, the performance of the theoretical bit error probability is roughly evaluated basing on the average bit error probability values with inner and outer Poincare spheres. The evaluated expression is

$$\hat{P}_{16} = \frac{p_{inner} + p_{outer}}{2} \qquad (8)$$

In (8), the values of P_{inner} and P_{outer} are calculated in terms of (7). We use the average bit power of the symbols located on the “inner Poincare sphere” and “outer Poincare sphere”. The theoretical value curve and the simulation results containing two kinds of 16 POLSK modulation scheme are plotted in the Fig.6. There have around 3.6 dB penalty if we demodulate the original SOP by Stokes parameter with respect to the second kind of 16 POLSK modulation scheme. Obviously, the ML demodulation scheme is better for this case. And all of the performance curves are not larger the upper boundary when the value of γ is not beyond 19 dB.

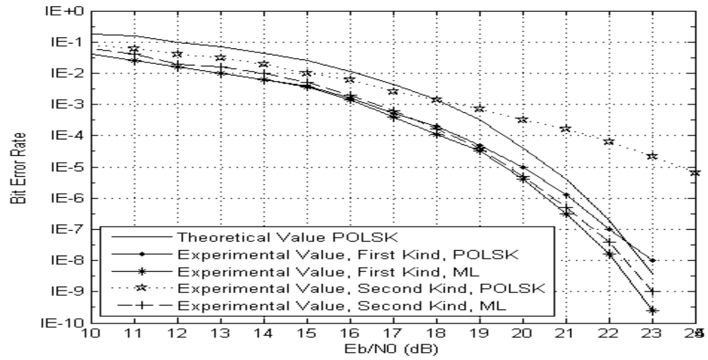

Fig. 6. Bit error rates for 16-ary constellation.

CONCLUSION

In this paper, a new POLSK modulation scheme with multi-envelop constellation structure are proposed. We design a simple POLSK communication system to verify the reasonable of application with a multi-envelop constellation structure. Computer simulation is carried out. Simulation results demonstrated that the experimental values are similar with the approximate theoretical values. Though the performance of the second kind 16 POLSK modulation with Stokes parameters detection is worse, the performance will be improved when the ML detection is exploited. And the system gain can reach around 3.6 dB.

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