IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 11 April 2023, accepted 8 May 2023, date of publication 12 May 2023, date of current version 19 May 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3275766

RESEARCH ARTICLE

A Novel 32-Point Modulation Scheme of 6PolSK-QPSK Signal

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This work was supported in part by the Natural Science Foundation of China under Grant 61901301, Grant 62001327, and Grant 62001328.

ABSTRACT The six-polarization shift keying quadrature (6PolSK-QPSK) has been proved to be an alternative to four-dimensional (4D) modulation scheme. A variety of transmission compensation schemes have been developed for 24-Point 6PolSK-QPSK combining the advantages of polarization multiplexing quadrature phase shift keying (PM-QPSK) and polarization switched quadrature phase shift keying (PS-QPSK). In order to further improve the transmission rate of the signal system, 32-Point 6PolSK-QPSK signal modulation has been studied. We propose a novel encoding rule and compensation scheme for 32-Point 6PolSK-QPSK modulation by classifying symbols. The simulation tool based on VPItransmissionMaker10.1 is equipped with 32-Point 6PolSK-QPSK signal transmission system and the off-line digital signal processing (DSP) module is applied to MATLAB to prove the method proposed in this paper. The simulation results show that the error performance of 2.6 dB and 8.7 dB are improved for unrevised and revised data transmission, compared with the 32-Point 6PolSK-QPSK signal scheme obtained by rotating PM-QPSK.

INDEX TERMS 6PolSK-QPSK, encoding rule, symbol classification, correction.

I. INTRODUCTION

With the development of coherent optical communication technology, high spectral efficiency (SE) modulation scheme is an important research direction. Polarization multiplexing quadrature phase shift keying (PM-QPSK) coherent optical transmission system combines polarization multiplexing technology, multi-base debugging technology, coherent detection technology and digital signal processing (DSP) technology, which has high SE, optical signal noise ratio (OSNR) sensitivity and moderate implementation complexity [1], [2], [3]. Polarization switched quadrature phase shift keying (PS-QPSK) coherent optical transmission system can be obtained by local adjustment on the basis of PM-QPSK system, and has been regarded as the simplest and the most energy efficient four-dimensional (4D) modulation scheme since it was proposed [4], [5], [6]. However, this signal modulation scheme has low spectrum utilization ratio. In order to combine the advantages of the two modulation schemes, six-polarization shift keying quadrature (6PolSK-QPSK) modulation scheme is proposed. It could be used as an alternative to PM-QPSK in a flexible-rate coherent modem [7].

So far, there have been a number of satisfactory transmission schemes for 24-Point 6PolSK-QPSK signal. In order to further increase SE, on the basis of 24-Point 6PolSK-QPSK (4.5 bits/symbol) signal, 32-Point 6PolSK-QPSK (5 bits/symbol) can be obtained. According to the signal characteristics of 32-Point 6PolSK-QPSK, the processing method of 24-Point 6PolSK-QPSK signal can be adopted. In order to obtain better transmission performance, 32-Point 6PolSK-QPSK transmission can be carried out by symbol classification. This paper mainly proposes a 6PolSK-QPSK encoding rule and a compensation scheme. The signal system is processed with VPItransmissionMaker10.1 and offline processing is carried out by MATLAB. The simulation results show

The associate editor coordinating the review of this manuscript and approving it for publication was Rentao Gu.

that compared with other signal modulation methods, the proposed method can achieve data transmission of 50-Gbps and improve the system performance of bit error ratio (BER).

The rest structure of this paper is as follows: in Section II, the encoding rule of 32-Point 6PolSK-QPSK is explained. In Section III, according to the characters of the signal, distortion compensation methods are introduced. In Section IV, based on the analysis in the above sections, the system simulation experiment of 32-Point 6PolSK-QPSK signal and analysis are carried out. Finally, the paper is concluded in Section V.

II. ENCODING RULE OF 6POLSK-QPSK

Poincare-sphere is a very intuitive and practical representation of polarized light. The signal can be modulated so that it can be properly placed on the Poincare-sphere to transmit information more efficiently and improve SE. The states of the modulated optical signal on the Poincare-sphere are concentrated at the six poles. Fig. 1 shows these states of polarization (SOP) in detail. PM-QPSK and PS-QPSK occupy 4 and 2 polarization states respectively. At the same time, each polarization state has 4 phase levels, so their constellations have 16 and 8 points respectively. The 24-Point 6PolSK-QPSK is the combination of PM-QPSK and PS-QPSK. Thus, it occupies 6 polarization states and has 24 different constellation points. For 32-Point 6PolSK-QPSK, it contains two sets of polarization states combination and each set contains 4 polarization states. Thus, a total of 8 polarization states are used to form a 32-Point constellation. However, because left-handed circular (LHC) polarization and right-handed circular (RHC) polarization are shared between the two sets, 32-Point 6PolSK-QPSK occupies the same 6 SOP as 24-Point 6PolSK-QPSK, but it carries 32 different kinds of information (5 bits/symbol).

In reference [7], 32-Point 6PolSK-QPSK is generated by polarization rotation of PM-QPSK symbols ($C_{PM-QPSK}$). $C_{PM-QPSK(45^\circ)}$ is the set ($C_{PM-QPSK}$) after the 45-degree rotation. There are 32 states of the symbols before and after the rotation. $(E_{xI}, E_{xQ}, E_{yI}, E_{yQ})$ is used to describe the constellation point vector. $C_{32-Point}$ is used to represent the set of signal constellation points. But when decoding, the two polarization states need to be combined to determine whether the symbol is rotating, which has high complexity.

$$C_{PM-QPSK} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} (\pm 1, \pm 1) \\ (\pm 1, \pm 1) \end{bmatrix}. \tag{1}$$

$$C_{PM-QPSK(45^\circ)} = \begin{bmatrix} E_x' \\ E_y' \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix}. \tag{2}$$

$$C_{32-Point} = C_{PM-QPSK} \cup C_{PM-QPSK(45^\circ)} \tag{3}$$

where, $E_x = (E_{xI}, E_{xQ})$ and $E_y = (E_{yI}, E_{yQ})$.

In order to facilitate decoding, we propose another novel 32-Point 6PolSK-QPSK encoding rule by classifying symbols. The combination of PM-QPSK and PS-QPSK constellation point sets can obtain the 24-Point 6PolSK-QPSK symbol set [8]. On this basis, the QPSK symbols are analyzed as follows.

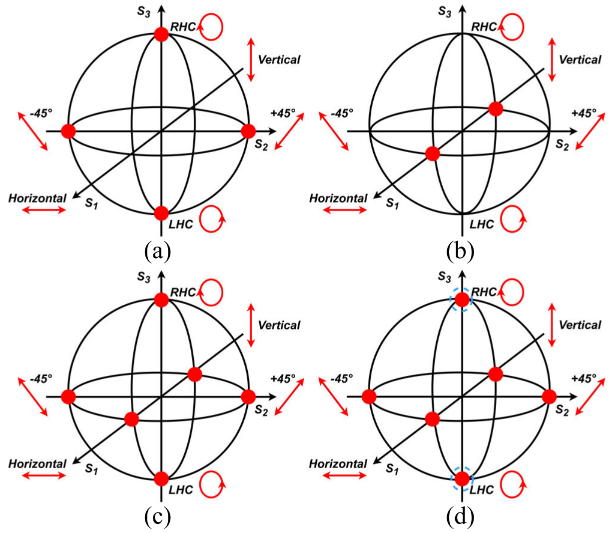

FIGURE 1. Poincare-sphere of (a) PM-QPSK (b) PS-QPSK (c) 24-Point 6PolSK-QPSK (d) 32-Point 6PolSK-QPSK. (Horizontal polarization, Vertical polarization, ±45° linear polarization, left-handed circular (LHC) polarization, right-handed circular (RHC) polarization).

Another constellation point set of PM-QPSK is set to C_1. C_2 can be used as a representation of PS-QPSK symbol [9]. Another representation of PS-QPSK can be obtained by rotation (45° polarization), which is set as C_3.

$$C_1 = \sqrt{2} \begin{cases} (\pm 1, 0, \pm 1, 0) \cup (0, \pm 1, \pm 1, 0) \\ (\pm 1, 0, 0, \pm 1) \cup (0, \pm 1, 0, \pm 1) \end{cases}. \tag{4}$$

$$C_2 = \sqrt{2} \begin{cases} (\pm 1, \pm 1, 0, 0) \\ (0, 0, \pm 1, \pm 1) \end{cases}. \tag{5}$$

$$C_3 = \begin{cases} [\pm(+1, +1, +1, +1)] \cup [\pm(+1, +1, -1, -1)] \\ [\pm(+1, -1, +1, -1)] \cup [\pm(+1, -1, -1, +1)] \end{cases} \tag{6}$$

According to the sign sets of PM-QPSK and PS-QPSK, the representation of 32-Point 6PolSK-QPSK can be obtained. Fig. 2 illustrates the 32-Point 6PolSK-QPSK modulation using two mutually orthogonal polarization states (X, Y).

Fig. 3 illustrates the novel encoding rule for 32-Point 6PolSK-QPSK in this paper. The transmission PM-QPSK or PS-QPSK is determined according to the first digit. When the first is 0, the following symbol is PM-QPSK (C_1). If not and the second is 0, the following is PS-QPSK (C_2). If the first two is 1, the symbol is PS-QPSK (C_3). The data is encoded in MATLAB and the information is loaded into the optical modulator.

III. DISTORTION COMPENSATION SCHEME

After long distance transmission, the polarization of optical signal will change randomly. The frequency difference between the transmitter laser and local oscillators (LO) laser will also interfere with the signal. The solution used in the industry is the use of high-speed DSP technology to realize chromatic dispersion (CD), polarization mode dispersion

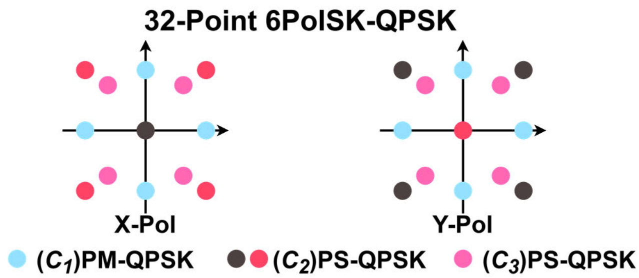

FIGURE 2. The constellation diagram of the two mutually orthogonal polarization states (X, Y).

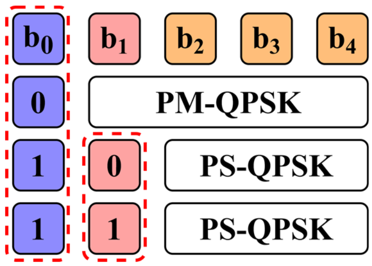

FIGURE 3. The encoding rule of 6PolSK-QPSK (5-bit).

(PMD), frequency, phase and other distortion compensation. Finally, symbolic decision is made to restore the original data. The following is the analysis of signal damage in transmission system and corresponding distortion compensation methods.

In practice, the I and Q channels in QPSK signal are not completely orthogonal due to offset of bias point, photodiode mismatch and other factors. Gram-Schmidt orthogonalization procedure (GSOP) is carried out to compensate the orthogonal imbalance between I channel and Q channel [10], [11].

The optical transmission link is affected by time-varying effects such as CD, PMD, polarization rotation [12], [13]. In order to reduce the complexity of the system implementation as much as possible, improve the dispersion compensation capability of the electric domain, and thus simplify or completely cancel the dispersion in the optical transmission link, two FIR filters with fixed coefficients are usually used to roughly equalize the CD damage in the two polarization states respectively. Then, a butterfly adaptive filter with a small number of taps is used to compensate PMD, residual CD damage and complete polarization demultiplexing [14], [15]. In the adaptive filter, the least mean square (LMS) algorithm is used to update the tap coefficient of adaptive filter [16], [17], [18], [19].

In the receiver of coherent optical transmission system, the feed-forward all digital phase frequency offset estimation algorithm is mainly used, such as the classical M times estimation algorithm. The M times operation of phase modulation information is implemented to remove the signal phase modulation. For 6PolSK-QPSK, M is 8. Since the adjacent QPSK symbols may jump, the compensation scheme mentioned in this paper adds phase jump detection on this basis, which can be referred to reference [20].

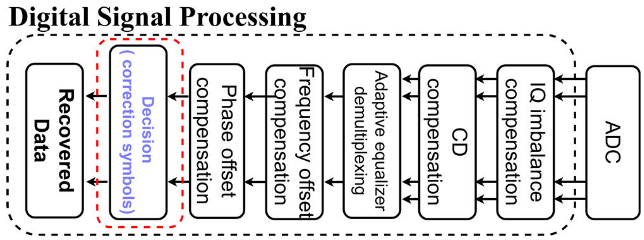

FIGURE 4. DSP module. The red dotted line is the signal compensation scheme (correction symbols) proposed in this paper.

The signal compensation scheme proposed in this paper is shown in Fig. 4. DSP module firstly uses GSOP algorithm to compensate the unbalanced state of I and Q channels, and then uses time-domain equalization algorithm to roughly equalize CD. The effect of PMD on optical signal is compensated by polarization demultiplexing. The frequency offset and phase noise of the lasers are compensated by the improved Viterbi algorithm. According to the signal characteristics of 32-Point 6PolSK-QPSK, the symbol decision is made, and data is finally recovered.

In the process of restoring the initial data by symbol decision (the red dotted line in Fig. 4), the symbols are determined by calculating the minimum Euclidean distance d_x and d_y between two polarization states of 6PolSK-QPSK symbol. However, there may be some symbol errors in this process. For example, $\sqrt{2}(+1, +1, 0, 0)$ may mistakenly become $(+1, +1, 0, 0)$. According to two sets of PS-QPSK symbols (C_2 and C_3), these errors can be easily identified and corrected.

$$R_x^2 + R_y^2 = \begin{cases} R_x^2 + R_y^2 < P_{x,y} \\ R_x^2 + R_y^2 = P_{x,y} \\ R_x^2 + R_y^2 > P_{x,y} \end{cases}. \tag{7}$$

The two polarization states (X, Y) after the symbols decision which is based on Euclidean distance d_x and d_y, are set to R_x and R_y respectively. There are two conditional judgments ($R_x^2 + R_y^2 < P_{x,y}$ and $R_x^2 + R_y^2 > P_{x,y}$) to correct the symbols which can be expressed as $(1, 1, 0, 0)$, $(0, 0, 1, 1)$ and other symbols that are not C_1, C_2 and C_3. When $R_x^2 + R_y^2 < P_{x,y}$, multiply the data coefficient satisfying this condition by $\sqrt{2}$. When $R_x^2 + R_y^2 > P_{x,y}$, multiply the data coefficient satisfying this condition by $\sqrt{2}/2$. When the condition $R_x^2 + R_y^2 = P_{x,y}$ is satisfied, this symbol does not need to be modified. $P_{x,y}$ whose value is 4 in this paper, is the power of the signal determined according to the driving voltage.

In symbol decision, add judgment conditions to correct errors. At the same time, because LMS algorithm takes some time to converge, there may be many errors in the initial stage of data recovery. For example, the symbol $(+1, +1, +1, +1)$ may mistakenly become the symbol $(+\sqrt{2}, 0, +1, +1)$ before the convergence of the algorithm is reached. After the convergence of the LMS algorithm, the two close PS-QPSK symbols on the constellation can converge towards the ideal signal points.

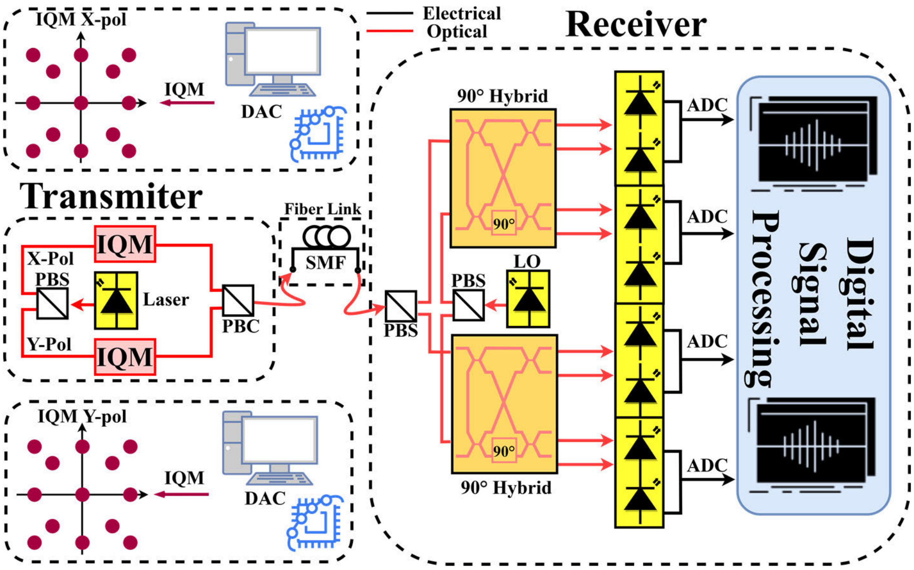

FIGURE 5. 32-Point 6PolSK-QPSK transmission system.

TABLE 1. Single mode fiber (SMF) Parameters.

Number	Parameters	Value
1	Transmission distance	100 km
2	PMD coefficient	0.2 ps/km$^{1/2}$
3	CD coefficient	16 ps/nm/km
4	Nonlinear coefficient	2.6e-20 m^2/W
5	Effective area	80.0e-12 m^2

IV. SIMULATION RESULTS AND DISCUSSION

In order to verify the effectiveness of the proposed signal compensation scheme, a 32-Point 6PolSK-QPSK simulation system is constructed according to Fig. 5 and the simulation parameters are described as follows.

We set the total amount of data transmitted to 655360 bits and the transmission rate to 50-Gbps. The imbalance angle of I and Q channels is set to 20°. The frequency offset between the two lasers is 500 MHz and the linewidth is 100 kHz. The optical fiber parameters are shown in Tab. 1. The launch power into optical fiber is −13 dBm. The gain of Erbium-doped fiber amplifier (EDFA) is set to 25 dB, and the noise factor is set to 10 dB.

The variable optical attenuator (VOA) is set to different values to simulate attenuation damage and obtain different received optical power (ROP). We set 10 different groups of VOA parameters (25-34 dB). The number of taps of the adaptive filter is set to 11, and the step size of the LMS algorithm is set to 0.0015. The sampling rate is set to double the symbol rate (10-Gbaud) throughout the DSP compensation process.

Through the above analysis, if the symbol correction is not added, the signal transmission of the system will be greatly affected. There are conditional judgments ($R_x^2+R_y^2 < 4, R_x^2+R_y^2 > 4$ and $R_x^2+R_y^2 = 4$) which determine whether to correct the symbols that are not C_1, C_2 and C_3. As shown in Fig. 6, Unrevised data (45°) and Revised data (45°) are the BER performance curves obtained by the signal modulation method in reference [7], and the red curves are the corresponding results obtained by the proposed method. Compared with the 32-Point 6PolSK-QPSK signal scheme obtained by rotating PM-QPSK signal with ROP from −21.5 to −12.5 dBm, the error performance of 2.6 dB and 8.7 dB are improved for unrevised data transmission and revised data transmission. The BER performance shows that the signal modulation method proposed in this paper has better system transmission performance.

Fig. 7 illustrates the constellation changes of the two polarization states of 32-Point 6PolSK-QPSK signal in the distortion compensation process. Fig. 7(a) and Fig. 7 (g) show the constellation diagram of X and Y polarization without DSP at the receiving end. According to the polarization states of the 6PolSK-QPSK signal, it can be found that the signal has been damaged. Fig. 7(b) - Fig. (f) show constellation diagram of X polarization state before symbols decision. Fig. 7(h) - Fig. 7(l) illustrate the signal distortion compensation process in Y-pol.

Combined with the 6PolSK-QPSK modulation scheme shown in Fig. 2, the recovery of the transmitted data is basically completed. The effectiveness of the proposed scheme is verified by the BER and constellation diagram after data recovery. In Section II, the compositions of 32-Point 6PolSK-QPSK with two different coding methods are analyzed. The reason why the coding method proposed in this paper is superior to the other coding method

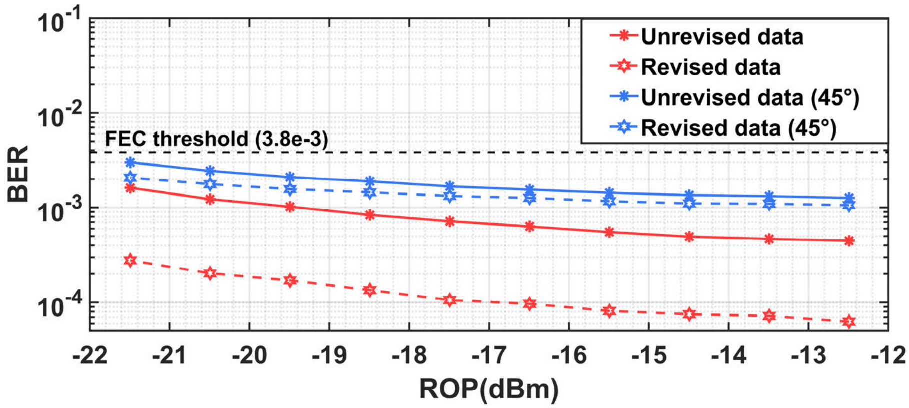

FIGURE 6. Unrevised data and revised data. Unrevised data is not subject to symbolic correction mentioned in this paper.

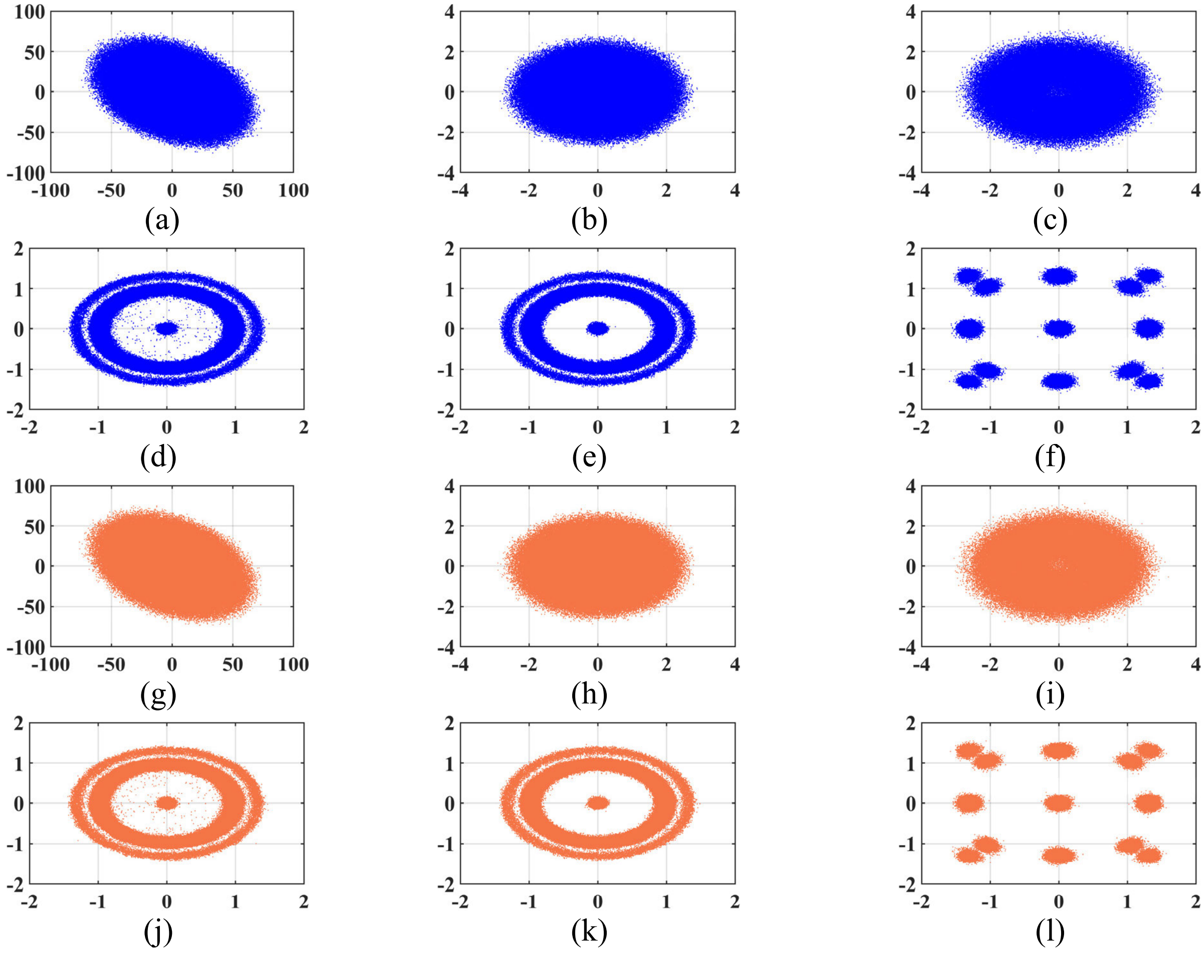

FIGURE 7. The constellations of X and Y polarization. X polarization: (a) Receiver received signal (b) IQ imbalance compensation (c) CD compensation (d) Adaptive equalizer demultiplexing (e) Frequency offset compensation (f)Phase offset compensation. Y polarization: (g) Receiver received signal (h) IQ imbalance compensation (i) CD compensation (j) Adaptive equalizer demultiplexing (k) Frequency offset compensation (l) Phase offset compensation.

can be analyzed in Fig. 8. According to the density of points, Fig. 8 (a) show the constellations on X polarization before the symbol decision, which are encoded in this paper. Fig. 8 (b) shows the constellations on X polarization obtained by the coding method in reference [7]. The symbols of PM-QPSK are chosen as C_1 to reduce the probability of symbol errors, so as to have better system performance.

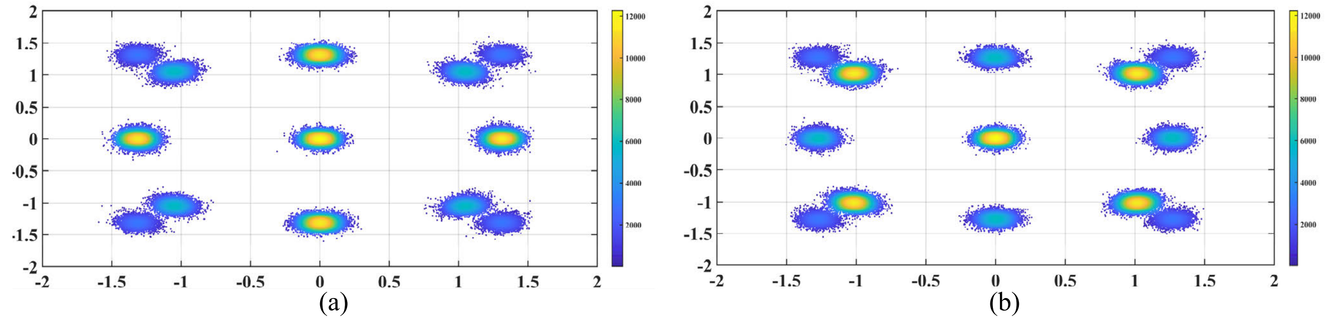

FIGURE 8. The constellations of X polarization of the 32-Point 6PolSK-QPSK signal before the symbol decision. (a) Through the symbol classification method in this paper, the constellation after phase offset compensation is completed. (b) According to the method in reference [7], the constellation after phase offset compensation is completed. (The color in the figure represents the density of the points and shows the composition of the signal).

V. CONCLUSION

A 32-Point 6PolSK-QPSK transmission scheme is proposed based on QPSK symbol classification (PM-QPSK and PS-QPSK). 50-Gbps data transmission is realized by the proposed encoding rule and compensation scheme. Compared with the 32-Point 6PolSK-QPSK signal scheme obtained by rotating PM-QPSK signal with ROP from −21.5 to −12.5 dBm, the error performance of 2.6 dB and 8.7 dB are improved for unrevised data transmission and revised data transmission. The results show that the proposed scheme could be used as an improvement of the rotating PM-QPSK scheme. Since the fixed step size of the traditional LMS algorithm will limit the compensation effect, we expect to use the modified LMS algorithm with variable step size to improve the BER performance of 32-Point 6PolSK-QPSK in the next step.

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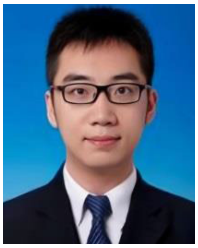

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