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RESEARCH

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Single-carrier transmission scheme for extracting characteristic parameters of 32-Point 6PolSK-QPSK

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Abstract

Six polarization-shift keying quadrature phase shift keying (6PolSK-QPSK) signal modulation format is formed by different representations of QPSK. A variety of satisfactory single-carrier transmission schemes have been implemented in 24-Point 6PolSK-QPSK. As an extension of 24-Point 6PolSK-QPSK, it has been confirmed that 32-Point 6PolSK-QPSK has higher spectral efficiency (SE). Based on the method of extracting 24-Point 6PolSK-QPSK feature parameters, a 32-Point 6PolSK-QPSK signal transmission scheme is proposed and verified in 100 km single-mode fiber (SMF) with an aggregate transmission rate of 108-Gbps. Simulation results show that the original data could be recovered effectively with the proposed scheme, and the system bit error ratio (BER) could meet the requirement of the forward error correction (FEC) threshold of 3.8e − 3.

Keywords: 6PolSK-QPSK, Compatible transmission scheme, LMS, Spectral efficiency

1 Introduction

Intensity modulation direct detection (IM/DD) is the most widely used transmission scheme at the early stage of the development of optical communication. However, the rapid growth of transmission rate requirement of communication system makes the development of IM/DD transmission scheme encounter a bottleneck. With the development of manufacturing technology of semiconductor devices and high-speed integrated circuit chips, coherent receiving technology has become a research hotspot again, and has rapidly developed into the mainstream receiver scheme of optical communication system.

Coherent optical reception refers to the use of a local oscillator (LO) laser at the receiving end to mix the received optical signals and obtain the electrical signals carrying transmission information through photoelectric conversion. Finally, these electrical signals are processed and the data information is recovered. Coherent optical receiving technology has high detection sensitivity, which means the transmission distance can be effectively increased. Furthermore, coherent reception is a holographic detection technology, which means that all features of optical signal, such as amplitude, frequency, phase and polarization state, could be used to carry information, thus the spectral efficiency (SE) can be significantly improved [1–3].

According to different requirements, different signal modulation formats can be selected for coherent optical communication. Higher SE is a fundamental research direction in all types of modulation schemes. Quadrature phase shift keying (QPSK) is a widely used digital modulation format, which has high frequency spectrum utilization, strong anti-interference and simple implementation on the circuit. Polarization-multiplexing quadrature phase shift keying (PM-QPSK) and polarization-switched quadrature phase shift keying (PS-QPSK) utilize the polarization states to transfer different kinds of information and obtain SE of 4 bit/symbol and 3 bit/symbol, respectively [4]. By combining their advantages, the 24-Point 6PolSK-QPSK with higher SE (4.5 bits/symbol) is obtained, whose principle and coding rule are based on PM-QPSK and PS-QPSK.

Since 24-Point 6PolSK-QPSK has been proposed, it has been proven to replace PS-QPSK and PM-QPSK [5–7]. So far, several satisfactory single-carrier transmission schemes have been proposed. In order to further increase the information carried by symbols and improve SE, a 32-Point 6PolSK-QPSK signal modulation scheme is proposed. In ref. [6], it has been proved to be an alternative to PM-QPSK and polarization-multiplexing 8-ary quadrature amplitude modulation (PM-8QAM) in flexible coherent modems. In this paper, a compensation scheme of 32-Point 6PolSK-QPSK signal single-carrier transmission is proposed. Simulation results show that the 32-Point signal with bit rate of 108-Gbps can be successfully transmitted under the forward error correction (FEC) limit of 3.8e-3.

The rest structure of this paper is as follows: In Sect. 2, the principle of 32-Point 6PolSK-QPSK modulation scheme and the coding rule is explained. In Sect. 3, an algorithm for digital equalization and damage compensation are introduced. In Sect. 4, the simulation system of 32-Point 6PolSK-QPSK signal is setup and the results analysis is carried out. Section 5 is the conclusion.

2 The principle of 32-Point 6PolSK-QPSK modulation format

There are six special poles on the Poincare-sphere, which representing the six polarization states of the light carrier, including left-handed circular (LHC) polarization, right-handed circular (RHC) polarization, vertical polarization, horizontal polarization and ± 45°linear polarization. PM-QPSK uses four of these poles, while the remaining two poles (horizontal and vertical polarization) are used by the PS-QPSK scheme. Each PS-QPSK symbol carries 3 bits of information, of which 2 bits are loaded on the QPSK symbol, and 1 bit determines whether the X or Y polarization of the optical carrier is used. X and Y polarization are completely staggered, and only one polarization component transmits valid information in transmission. PS-QPSK signal can be generated at 25% of the cost for compatibility with PM-QPSK system hardware [8]. 24-Point 6PolSK-QPSK, which occupies 6 states of polarization (SOP), is the combination of PM-QPSK and PS-QPSK mentioned above. According to the characteristics of the signal, 32-Point 6PolSK-QPSK has the same SOP as 24-Point 6PolSK-QPSK. The modulation principle of the signal is explained below.

$$C_{\mathrm{PM}} = \sqrt{2}\left\{[(\pm1,0)\ \text{or}\ (0,\pm1)]_{X-\mathrm{pol}} \cup [(\pm1,0)\ \text{or}\ (0,\pm1)]_{Y-\mathrm{pol}}\right\}. \tag{1}$$

$$C_{\mathrm{PS}} = \sqrt{2}\left\{[(\pm 1, \pm 1)_{X-\mathrm{pol}} \cup (0,0)_{Y-\mathrm{pol}}] \cup [(0,0)_{X-\mathrm{pol}} \cup (\pm 1, \pm 1)_{Y-\mathrm{pol}}]\right\}. \tag{2}$$

$$C_{\mathrm{PS}(45^\circ)} = \left\{ \begin{array}{l} [\pm(+1,+1)]_{X-\mathrm{pol}} \cup [\pm(+1,+1)]_{Y-\mathrm{pol}} \\ [\pm(+1,-1)]_{X-\mathrm{pol}} \cup [\pm(+1,-1)]_{Y-\mathrm{pol}} \end{array} \right\}. \tag{3}$$

The link damage in the optical transmission system has little influence on the same amplitude signal. In order to generate the 6PolSK-QPSK equal amplitude signal, PM-QPSK and PS-QPSK at the same average transmission power are expressed as Eq. 1 to Eq. 3, which can be represented by C_{PM}, C_{PS} and $C_{\mathrm{PS}(45^\circ)}$. $C_{\mathrm{PS}(45^\circ)}$ is obtained by rotating C_{PS} with 45°polarization. Figure 1a illustrates the relationship between their two orthogonal polarization states. The 32-Point 6PolSK-QPSK modulation scheme is generated by combining PM-QPSK and PS-QPSK. PS-QPSK transmits 16 different kinds of information by whether it is rotated or not, which is combined with PM-QPSK signal to generate 32 states of 6PolSK-QPSK. Two groups of 4 SOP are included in 32-Point 6PolSK-QPSK, but LHC polarization and RHC polarization are shared between the groups. This is why 32-Point 6PolSK-QPSK and 24-Point 6PolSK-QPSK have same SOP. Figure 1b shows the coding rules of 32-Point 6PolSK-QPSK. Compared with 24-Point 6PolSK-QPSK, a symbol can be encoded with 5 bits of information. We first determine whether it is PM-QPSK or PS-QPSK based on the first symbol bit. When the first bit is 0, the PM-QPSK symbol is transmitted; otherwise PS-QPSK symbol is transmitted. The PS-QPSK symbol determines rotation based on the second bit. If the second bit is 0, the code is C_{PS}. When the second bit is 1, PS-QPSK (C_{PS}) is rotated to transmit $C_{\mathrm{PS}(45^\circ)}$.

3 Compensation scheme

3.1 Adaptive equalization

In order to simplify or cancel chromatic dispersion (CD) compensation in optical transmission link, two finite impulse response (FIR) filters with fixed coefficients are generally used to compensate CD under the condition of reducing the complexity of system implementation, so as to enhance the ability of dispersion compensation in electric domain. In order to realize polarization demultiplexing and compensate the influence of polarization mode dispersion (PMD) on the signal, a butterfly structure of cross-polarization interference cancellation (XPIC) is composed of four FIR filters [9, 10]. Each FIR

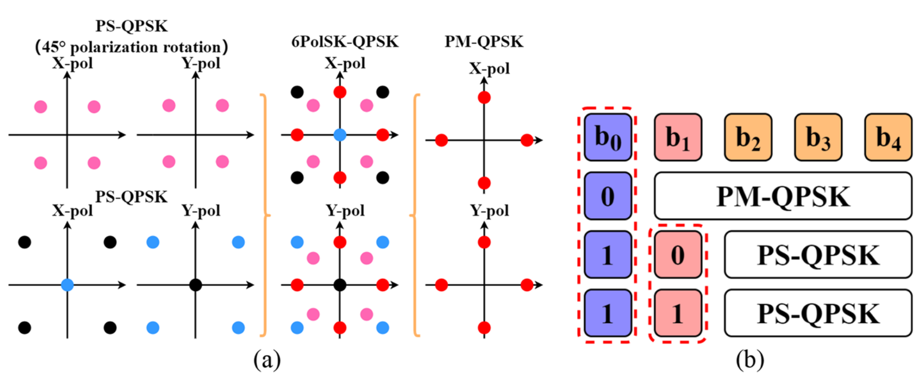

Fig. 1 **a** Polarization states (*X* and *Y*) of PS-QPSK, 6PolSK-QPSK, PM-QPSK. **b** The coding rule of 32-Point 6PolSK-QPSK

filter of butterfly adaptive filter has several taps, and increasing the number of taps can enhance the effect of PMD compensation accordingly.

In the process of adjusting the tap coefficient of the filter, it is necessary to use the corresponding adaptive equalization algorithm. The constant modulus algorithm (CMA) [11] and the least mean square algorithm (LMS) [12, 13] are two algorithms frequently used by scholars. CMA is a blind equalization algorithm, which makes use of the principle that the moduli of PSK modulation signal remain constant. By adjusting the tap coefficient of filter, the moduli of output signal approximate to the reference moduli. This algorithm can be well used in PM-QPSK modulation schemes. However, 6PolSK-QPSK signal is not a constant mode value. Therefore, the CMA algorithm can only compensate part of the 6PolSK-QPSK signal and the LMS algorithm is also needed for compensation. 24-Point 6PolSK-QPSK has a filter tap coefficients updated method according to the LMS algorithm in ref. [5]. Combined with the constellation diagram in Fig. 1a, 32-Point 6PolSK-QPSK also meets the use conditions.

$$P = \begin{pmatrix} P_x \\ P_y \end{pmatrix} = \begin{pmatrix} (4,0,2) \\ (0,4,2) \end{pmatrix}. \tag{4}$$

$$\varepsilon_x = P_x - |X_{\text{out}}|^2. \tag{5}$$

$$\varepsilon_y = P_y - |Y_{\text{out}}|^2. \tag{6}$$

According to Eqs. 1 to 3 the power sets (Eq. 4) on the two polarization states (X-pol and Y-pol), and the corresponding error functions (Eq. 5 and Eq. 6) can be obtained. $P_{x,y}$ and $\varepsilon_{x,y}$ are the power and error in the corresponding polarization state (X-pol and Y-pol), respectively. X_{out} and Y_{out} are the output of the equalizer. Since the value ($P_{x,y}$) corresponds to three possibilities, the minimum joint error is introduced to determine the reference power value, $\delta_{\min}$ is represented as follows:

$$\delta_{\min} = \min(\varepsilon_x^2 + \varepsilon_y^2). \tag{7}$$

As Fig. 2 shown, 32-Point 6PolSK-QPSK signal has three reference modes in two polarization states (X-pol and Y-pol). By minimizing the joint error, the corresponding reference modulus value of the data can be obtained, so as to update the filter tap coefficient.

The filter tap coefficients update method can be expressed as follows:

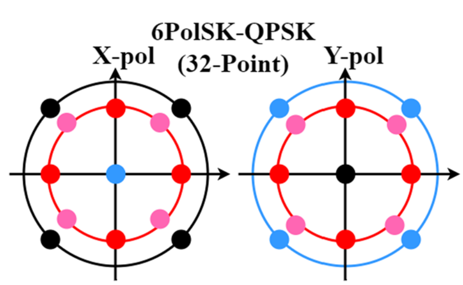

Fig. 2 32-Point 6PolSK-QPSK with different reference modulus in *X* and *Y* polarizations

$$\begin{pmatrix} h_{xx} & h_{xy} \\ h_{yx} & h_{yy} \end{pmatrix} = \begin{pmatrix} h_{xx} + 2\mu\varepsilon_x X_{\text{in}} X_{\text{out}}^* & h_{xy} + 2\mu\varepsilon_x Y_{\text{in}} X_{\text{out}}^* \\ h_{yx} + 2\mu\varepsilon_y X_{\text{in}} Y_{\text{out}}^* & h_{yy} + 2\mu\varepsilon_y Y_{\text{in}} Y_{\text{out}}^* \end{pmatrix}. \tag{8}$$

where h_{ij} represents tap coefficients of four filters. μ is the iteration step. X_{in}^* and Y_{in}^* are complex conjugates of input signal X_{in} and Y_{in}, respectively.

3.2 Offset compensation

In the coherent optical communication system, the received optical signal is detected by the coherent detection technology. The frequency deviation between the laser at the transmitter and the LO laser at the receiver and the phase noise caused by the linewidth of the laser will lead to the phase error of the signal. In general, the offset compensation is performed after polarization demultiplexing is completed.

Taking PM-QPSK modulation scheme as an example, the most common processing method is the joint application of the fourth power frequency offset estimation algorithm and the Viterbi–Viterbi (V–V) algorithm [14–17]. Theoretically, the phase difference between adjacent symbol bits of the received signal is an integer multiple of $\pi/2$, then the phase difference of four times is an integer multiple of 2π, and the frequency offset compensation is realized. After frequency offset compensation, signal carrier phase compensation continues to be carried out. Due to the great difference between the change rate of carrier phase and the rate of phase modulation, the change of optical carrier phase could be ignored, and the default value is fixed. For the PM-QPSK modulation scheme, the phase difference of different modulation states is an integer multiple of $\pi/2$, then the quadruple phase difference is an integer multiple of 2π. Four times of the phase error of the code can be obtained by summing and averaging multiple symbols. Finally, the carrier phase error is obtained and used to recover the modulated signal.

On the basis of PM-QPSK, the eighth power method could be used to compensate the frequency offset estimation and phase noise according to the characteristics of the signal constellation diagram of 32-Point 6PolSK-QPSK. Since the phase calculated by the angular calculation is within $(-\pi, \pi]$, the effective estimated value is limited to $(-\pi/8, \pi/8]$, which needs to be adjusted by adding a detection module [18].

Figure 3 shows the principle of the detection module, which determines whether phase correction is needed according to the phase difference between the two data blocks before and after. C is the phase estimate of the data block. Each data block has

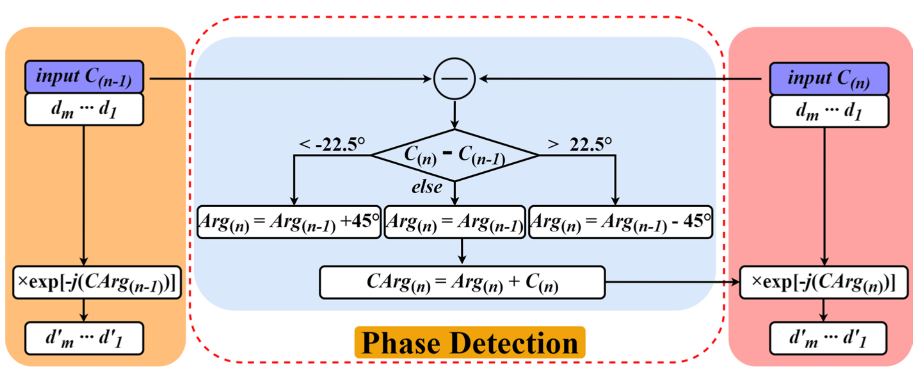

Fig. 3 Phase detection of 32-Point 6PolSK-QPSK with the eighth power

m data ($d_1 \cdots d_m$). d' is the output data after phase compensation is completed. $\mathrm{Arg}_{(n)}$ is the accumulated value of phase error up to the nth data block. $\mathrm{CArg}_{(n)}$ is the estimated value of the phase to be compensated up to the nth block.

4 Simulation results and discussion

In order to evaluate the effectiveness of compensation scheme proposed in this paper, a simulation tool based on VPItransmissionMaker 10.1 is equipped with 32-Point 6PolSK-QPSK signal transmitter, optical transmission link and coherent receiver model.

Figure 4 is the block diagram of the transmission system of 6PolSK-QPSK signal with CD, PMD, frequency offset, phase offset and other signal damage. The modulator driving signals are generated in MATLAB according to the coding rule in Fig. 1b. Mach–Zehnder modulator working mode is set to push–pull. The linewidth of two lasers (Laser and LO) is set to 100 kHz and their frequency deviation is set to 500 MHz. The data amount, hybrid deviation, transmission distance and transmission rate are set as 655,360 bits, 20°, 100 km and 108-Gbps, respectively. The CD coefficient, nonlinear coefficient, effective area, and PMD coefficient are set as 16 ps/nm/km, 2.6e-20 m^2/W, 80.0e-12 m^2, 0.2 ps/$km^{1/2}$, respectively. The received optical power (ROP) is 0 dBm. 55 filter taps are used in adaptive equalizer demultiplexing module and the iteration step μ is set to 2.5e-4.

Figure 5 shows the two orthogonal polarization states constellation diagram of 32-Point 6PolSK-QPSK after running the compensation scheme. The density of the scatter is calculated, and the color is divided according to the density. The symbol composition of 32-Point 6PolSK-QPSK is also explained (50% PM-QPSK and 50% PS-QPSK).

Figure 6 shows the performance of BER under the condition of different optical signal to noise ratio (OSNR), the FEC threshold limit (3.8e-3) could be met when OSNR is larger than 24 dB. The simulation results shows that the compensation scheme mentioned in this paper could be used to recover 32-Point 6PolSK-QPSK effectively. It is

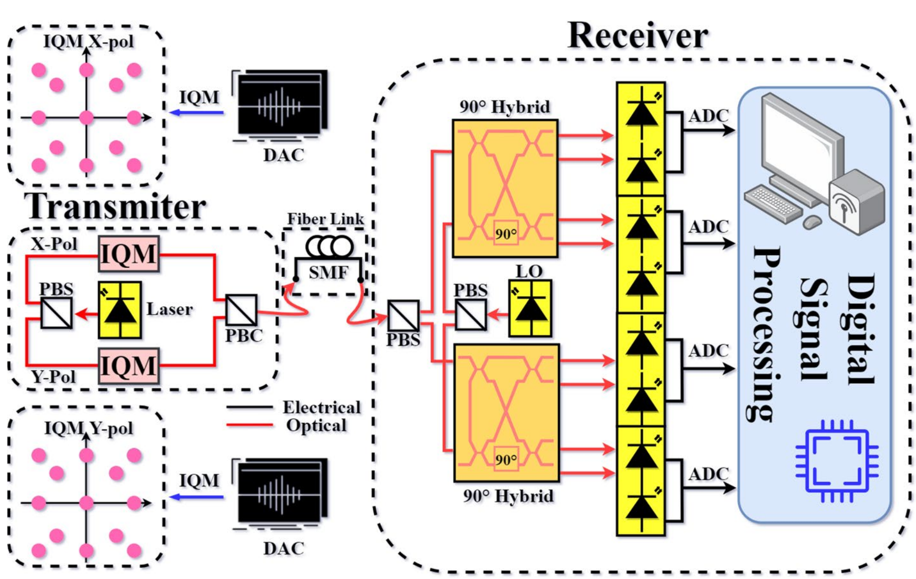

Fig. 4 32-Point 6PolSK-QPSK transmission system (transmitter, fiber link and receiver)

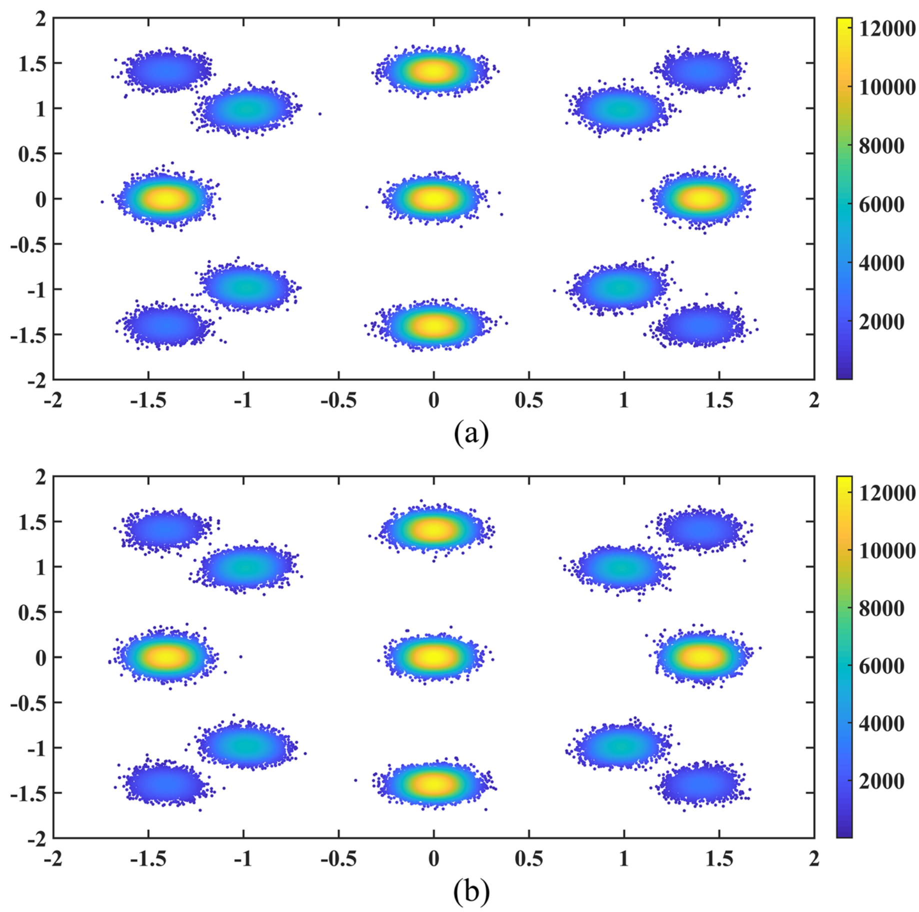

Fig. 5 The polarization states constellation diagram of **a** *X*-pol **b** *Y*-pol after running the compensation scheme (OSNR 30 dB)

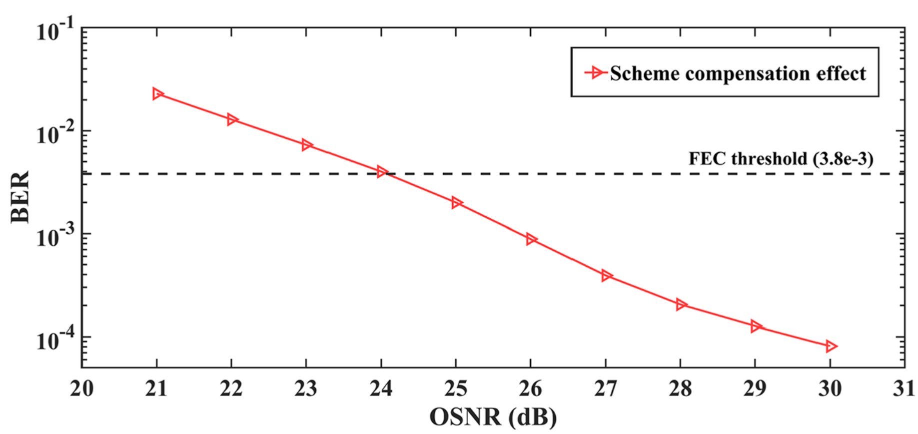

Fig. 6 BER performance with different OSNR coefficients

worth noting that the compensation scheme mentioned in this paper uses a constant step size. The convergence speed and accuracy of the LMS algorithm are related to the step size. Traditional LMS algorithm can only make trade-offs between convergence speed and steady-state error, but cannot achieve fast convergence and small steady-state error at the same time. The larger the step size, the faster the convergence speed, but the larger the error in the steady state. Conversely, the smaller the step size, the slower the convergence speed, but the smaller the steady-state error. Therefore, the fixed step size will affect the effectiveness of the filter.

5 Summary

In this paper, the principle of 32-Point 6PolSK-QPSK (5 bit/symbol) modulation scheme is introduced, and an optical signal compensation scheme is proposed. The simulation results show that the proposed scheme can complete data recovery within the effective FEC threshold (3.8e-3) when the 108-Gbps 32-Point 6PolSK-QPSK signal is transmitted. In the traditional fixed-step LMS algorithm, the step factor is a constant and does not change with the convergence state during the whole process from the initial stage of convergence to the steady state. The variable step size LMS equalizer has faster convergence speed and can timely adapt to the constantly changing transmission channel. We hope to apply the adaptive algorithm to the 6PolSK-QPSK with 32 points in the next step.

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Author contributions
All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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