



Three dimensional amplitude modulation and demodulation technology based on independent dual sideband optical communication system

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ABSTRACT

This article proposes the use of Three Dimensional Amplitude Modulation (TDAM) and demodulation techniques in independent dual sideband systems without increasing the modulation order of the carrier amplitude. This system generates two columns of random binary sequences digitally. One is modulated with 3D-8QAM at -13 GHz, and the other is modulated with 3D-8QAM at 29 GHz with half amplitude. Then, the three dimensions x , y , and z of the three-dimensional signal are modulated onto the carriers $\cos(\omega t)$, $\sin(\omega t)$ and $\cos(\omega t) \cdot \sin(\omega t)$, respectively, so that the left and right independent sidebands are superimposed in the IQ modulator. At the receiving end, two independent sideband signals are received through a single photodiode (PD). After PD square law conversion, a three-dimensional 8TDAM signal is synthesized, and then separated and demodulated by a digital signal processing (DSP) to obtain two separate three-dimensional signals. The simulation results show that the system can successfully achieve 8 Gbaud independent 8TDAM signal 20 km SSMF transmission, with an HD-FEC threshold of 3.8×10^{-3} and an error rate of 7 %. The system has demonstrated that three-dimensional signals can be transmitted independently in both sidebands, greatly simplifying the system structure, further reducing implementation costs, and improving spectral efficiency. The highest spectral efficiency can reach 3.692bit/s/Hz.

1. Introduction

With the rapid development of 5G technology, various high-tech technologies such as virtual reality, artificial intelligence, cloud services for smart cities, the Internet of Things, big data, etc. have exploded like mushrooms after rain. While bringing more convenience to people's lives, they have also put forward higher requirements for the overall capacity of the network and the improvement of transmission speed. In order to further improve the transmission distance, system capacity, spectrum efficiency and other performance of fiber optic communication systems, modulation and demodulation technologies such as orthogonal amplitude modulation (QAM) [1], frequency shift keying (FSK), phase shift keying (PSK), amplitude shift keying (ASK), and grid coding modulation (TCM) have emerged. At the same time, researchers are also seeking more efficient and advanced coding and modulation technologies as well as higher-order multi-dimensional modulation formats.

Modulation and demodulation technology is a key technology in communication systems, which maps information sequences into

modulated signals for transmission over communication channels [2]. More efficient and advanced high-order multi-dimensional modulation technology is mainly reflected in two aspects: increasing the modulation order [3–5] and increasing the modulation dimension [6–9]. Among them, high-order orthogonal amplitude modulation techniques have been widely studied and applied. If the modulation order is forcibly increased, the transmission power of the signal will be increased to the point where it cannot be achieved while ensuring the bit error rate (BER). On the other hand, in terms of increasing modulation dimensions, traditional modulation methods carry different information by adjusting one or more parameters. For example, the one-dimensional degree of freedom modulation method ASK transmits information by adjusting the amplitude of the signal, PSK transmits information by adjusting the phase of the signal, and FSK transmits information by adjusting the frequency of the signal; The two-dimensional degree of freedom modulation method QAM transmits information by adjusting the amplitude and phase of the transmitted signal. Based on this, researchers have proposed a multi-dimensional modulation format, which expands the dimensions of the modulation format by adding one-dimensional

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degrees of freedom, achieving a leap from two-dimensional modulation formats to three-dimensional or even higher dimensional modulation formats, thereby improving the spectral efficiency and noise tolerance of fiber optic communication systems. The high-speed baseband digital modulation and demodulation technology with three-dimensional degrees of freedom has always been a high-tech pursued by the industry. Improving modulation rate by increasing modulation freedom without increasing the modulation order of the carrier amplitude and with less increase in channel signal-to-noise ratio has always been a technical focus of 3D modem research.

The parameters of the multi-dimensional degree of freedom modulation format include amplitude, phase, frequency, direction, polarization mode, etc. Traditional modulation methods such as ASK and QAM only use one or two parameters such as amplitude or phase as modulation variables. Therefore, in order to carry more information in the transmission signal and achieve a three-dimensional degree of freedom modulation format, researchers have proposed adding polarization as a new parameter to achieve joint modulation of the amplitude, phase, and polarization parameters of the electromagnetic wave signal. Based on this, some new modulation methods, such as Polarization Shift Keying (PolSK), have been proposed and studied. This modulation method introduces two polarization parameters into PSK modulation to form a new three-dimensional modulation method. With the popularity of high-speed baseband digital modulation and demodulation technology with three-dimensional degrees of freedom in practical applications, more and more researchers are participating in the study of polarization technology. For example, in 2005, Li Chao and Kuo Yonghong introduced a design and implementation method for QAM signal recognition based on polarization modulation [10]. In 2012, Song Hanbin from Fudan University proposed three-dimensional modulation methods such as polarization amplitude phase modulation (PAPM) and polarization amplitude modulation (PQAM). After further studying the methods of utilizing polarization differences of electromagnetic waves for wireless communication [11], we found that reasonable utilization of polarization information of electromagnetic waves can effectively improve the performance of wireless communication systems, significantly increase the channel capacity of wireless communication systems [12,13], and using polarization information to control power amplifiers can improve modulation efficiency [14,15]. In addition, electromagnetic polarization information has also played a significant role in phased array radar, improving radar signal detection resolution, and beamforming [16].

However, in the aforementioned three-dimensional modulation, it is necessary to simultaneously adjust three signal parameters. For example, PolSK requires simultaneous adjustment of phase and two polarization state parameters, PAPM requires simultaneous modulation of polarization state, amplitude, and phase parameters, and PQAM requires simultaneous adjustment of polarization angle, amplitude, and phase parameters. The joint modulation of three parameters greatly increases the complexity and implementation difficulty of fiber optic communication systems. The three-dimensional polarization modulation technology based on increasing polarization parameters, which is studied in existing literature, performs three-dimensional joint modulation and demodulation of wireless signal amplitude, polarization angle, and polarization phase angle at the transmitting end [17–19], and demodulates three-dimensional joint modulation signals at the receiving end through signal amplitude detection and direction of arrival (DOA) polarization parameter estimation. Although simulations have shown that this technology has the advantages of high transmission rate, low bit error rate, and high-order digital modulation capability to carry high transmission rates. However, the complexity of its modulation technology, especially demodulation technology, violates the design concept of simple and low-energy terminal systems required by 5G systems, which greatly limits its development in the field of mobile communication, at least in the short term, and cannot be applied in the field of mobile communication.

Therefore, in this article, we propose and simulate a Three Dimension

Amplitude Modulation (TDAM) technology based on an independent dual sideband system. Without increasing the modulation order of the carrier amplitude and polarization parameters, this scheme only adds one modulation carrier function $\cos(\omega t) \cdot \sin(\omega t)$ to expand the information carrying capacity of the transmission signal, and it does not require the three-way modulation carrier functions to be orthogonal to each other, greatly simplifying the complexity of existing research results. It is easy to implement, simple and even directly applicable in reality. This system generates two columns of random binary sequences using digital methods, and modulates the left and right bands using the three-dimensional 8QAM modulation method. Then, the three dimensions x , y , and z of the three-dimensional signal are modulated onto the carriers $\cos(\omega t)$, $\sin(\omega t)$ and $\cos(\omega t) \cdot \sin(\omega t)$, respectively. x and y are used as the real and imaginary parts to form $x + yi$, and z and 0 are also used as the real and imaginary parts to form $z + 0i$. The two parts are linearly added to achieve the transmission of the three-dimensional signal to the IQ modulator, so that the left and right independent sidebands are superimposed in the IQ modulator. At the receiving end, two independent sideband signals are received through a single photodiode. After PD square law conversion, a three-dimensional 8TDAM signal is synthesized, and then separated and demodulated through digital signal processing to obtain two separate three-dimensional signals. The simulation results show that the length of the two pseudo-random binary sequences generated by the offline end of the system is 2^{14} . One is modulated by 3D-8QAM at -13 GHz, and the other is modulated by 3D-8QAM at 29 GHz with half amplitude. At the transmission end, an external cavity laser (ECL) with a linewidth less than 100 kHz is used to generate a continuous wave (CW) light wave. The ECL operates at a frequency of 193.10 THz, with a CW wavelength of 1548.705 nm (C-band) and an output optical power of -13 dBm. It can successfully transmit 2 Gbaud, 4 Gbaud and 8 Gbaud independent 8TDAM signals BTB, 5 km, 10 km, and 20 km SSMF, with a bit error rate of 7% and an HD-FEC threshold of 3.8×10^{-3} .

The combination of this three-dimensional modulation and demodulation scheme with coherent detection not only expands the system capacity, but also greatly simplifies the system structure, further reduces the implementation cost and improves the spectral efficiency up to 3.692 bit/s/Hz, which is significantly higher than that of the traditional two-dimensional QAM modulation. It has a broad application prospect in the future construction of high-speed and large-capacity optical fibre communication system. In addition, since the algorithm of the digital signal processing unit at the receiving end can be used to perform laser phase noise compensation, this system also has potential applications in dealing with laser phase noise. Generally in coherent optical transmission systems, the asynchrony of the drift of the signal light frequency and the drift of the local oscillator light frequency will produce phase noise on the signal due to the different sources of signal light and local oscillator light. The laser linewidth will affect the signal phase, the larger the laser linewidth, the greater the impact on the signal, and the worse the signal performance, so that the signal phase needs to be corrected at the receiving end by phase correction algorithm. This system is carried out by direct modulation and direct detection, with the transmitting end directly loading the signal onto a laser through an IQ modulator to generate an optical signal. This system uses only one laser to generate one optical signal, and generates the optical sidebands of different frequencies through the IQ modulator. At the receiving end, a photodiode is used to generate the required sideband signal through mutual tapping. Due to the use of a laser, the linewidth of the laser has the same effect on all optical sideband signals. That is to say, when the optical signal frequency increases or decreases, it simultaneously has an increasing or decreasing effect on all sidebands, while the interval between the two sidebands remains unchanged, so that in direct modulation and direct detection, the laser's linewidth has little impact on the signal. Of course, it does not mean that the laser linewidth has no effect on the phase of the signal, but the phase noise generated by the laser linewidth is not as large as the phase noise of the coherent optical system

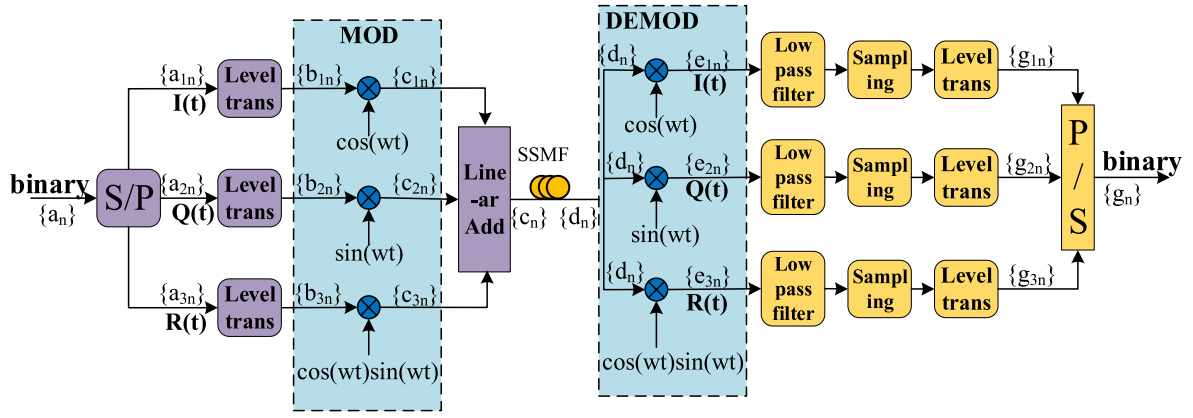


Fig. 1. Basic process of 3D TDAM modulation and demodulation.

signal. The direct-modulation direct-detection system we use is carried out by using electrical coherence at the receiving end, it down converts the signal into baseband through electrical coherence, and mixes the signal with a radio-frequency(RF) local oscillator source at the receiving end. The instability of the frequency of the RF local oscillator source has a great impact on the signal performance. We have conducted detailed research in this regard, and in Ref. [20], we have provided a detailed explanation of the impact of different degrees of RF local oscillator source frequency drift on the signal. There are many methods of phase correction algorithm and in this system, we use blind phase search (BPS) algorithm. BPS phase correction method finds the appropriate signal by rotating the signal to look for the shortest Euclidian distance from the required signal. BPS phase correction method can be suitable for most signals and can be applied in most communication transmission systems. In Ref. [21], based on the least mean square (LMS) method, Alamouti DSP is used to process the received signal for each subcarrier, so that residual phase noise is reduced in the process.

The remainder of this paper is organized as follows. In Section 2, the basic working principle of three-dimensional amplitude modulation and demodulation technology and the principle of synthesizing three-dimensional signals in independent dual sideband systems were introduced. In Section 3, the constellation diagram and bit error rate curve of 8TDAM technology were simulated and analyzed at different baud rates and transmission distances. Section 4 concludes the entire paper.

2. Principle

TDAM modem is a three-dimensional amplitude modulation and demodulation technology, which is very similar to QAM in principle yet has better modulation performance than QAM. Therefore, the technology is simple and easy to implement. However, due to the addition of one-dimensional modulation freedom on the basis of QAM, it can greatly improve the modulation rate of the system, and has the potential to become a new choice for baseband digital modulation in 5G systems.

The foundation of three-dimensional TDAM modulation and demodulation technology is the basic formula of trigonometric functions:

$$\sin(x) \cdot \sin(x) = (1 - \cos(2x))/2 \quad (1)$$

$$\cos(x) \cdot \cos(x) = (1 + \cos(2x))/2 \quad (2)$$

$$\sin(x) \cdot \cos(x) = \sin(2x)/2 \quad (3)$$

$$\sin(x) \cdot \cos(x) \cdot \sin(x) \cdot \cos(x) = (1 - \cos(4x))/8 \quad (4)$$

$$\sin(x) \cdot \sin(x) \cdot \cos(x) = (1 - \cos(2x)) \cdot \cos(x)/2 \quad (5)$$

$$\cos(x) \cdot \sin(x) \cdot \cos(x) = (1 + \cos(2x)) \cdot \cos(x)/2 \quad (6)$$

In the formula, the product of $\sin(x) \cdot \cos(x)$ and $\sin(x) \cdot \cos(x)$ can also separate the DC term, while the product of $\sin(x) \cdot \cos(x)$ and $\sin(x)$ or $\cos(x)$ only has the AC term. Therefore, through low-pass filtering, the amplitude DC term of the carrier signal can also be filtered out using equation (4).

The basic principle of 3D-TDAM modulation and demodulation is shown in Fig. 1. Obviously, just like the working principle of 2D 8QAM, it only adds one-dimensional degrees of freedom. At the transmitting end, the binary data stream $\{a_n\}$ is serially and parallelly transformed into three binary data streams $\{a_{1n}\}$, $\{a_{2n}\}$ and $\{a_{3n}\}$. The three data streams are allocated four level values of 2 bits to achieve 2–4 level transformation, making them the new data streams $\{b_{1n}\}$, $\{b_{2n}\}$ and $\{b_{3n}\}$. Then, three carriers $\cos(\omega t)$, $\sin(\omega t)$ and $\cos(\omega t) \cdot \sin(\omega t)$ are used to modulate these three signals into carrier modulated data streams $\{c_{1n}\}$, $\{c_{2n}\}$ and $\{c_{3n}\}$, and finally linearly superimpose the three modulated data streams into $\{c_n\}$, which are sent out from the SSF; At the receiving end, the signal $\{d_n\}$ is transmitted through SSFs and added with noise. The receiving system also uses carriers $\cos(\omega t)$, $\sin(\omega t)$ and $\cos(\omega t) \cdot \sin(\omega t)$ to demodulate $\{d_n\}$, and separate it into three signals $\{e_{1n}\}$, $\{e_{2n}\}$ and $\{e_{3n}\}$, and then recover them into three data signals $\{g_{1n}\}$, $\{g_{2n}\}$ and $\{g_{3n}\}$ through low-pass filtering, sampling decision, and 4-2 level transformation. Finally, combine them into one data signal $\{g_n\}$ output through parallel series transformation.

This study suggests that in multi-dimensional amplitude modulation and demodulation technology, the orthogonality between modulation carriers has little impact on the modulation and demodulation process. As is well known, the orthogonality of a function is a very important property of a function, defined as: if two functions $\psi_1(x)$ and $\psi_2(x)$ meet the condition:

$$\int \psi_1(x) \cdot \psi_2(x) dx = 0 \quad (7)$$

Then these two functions are said to be orthogonal to each other. Set up $\psi_1(x) = \sin(x)$, $\psi_2(x) = \cos(x)$, $\psi_3(x) = \sin(x) \cdot \cos(x)$, then the definite integral within the interval $[a, b]$ is:

$$\int_a^b \psi_1(x) \psi_2(x) dx = \int_a^b \sin(x) \cdot \cos(x) dx = \int_a^b \sin(x) d(\sin(x)) = \frac{1}{2} \sin^2(x) \Big|_a^b \quad (8)$$

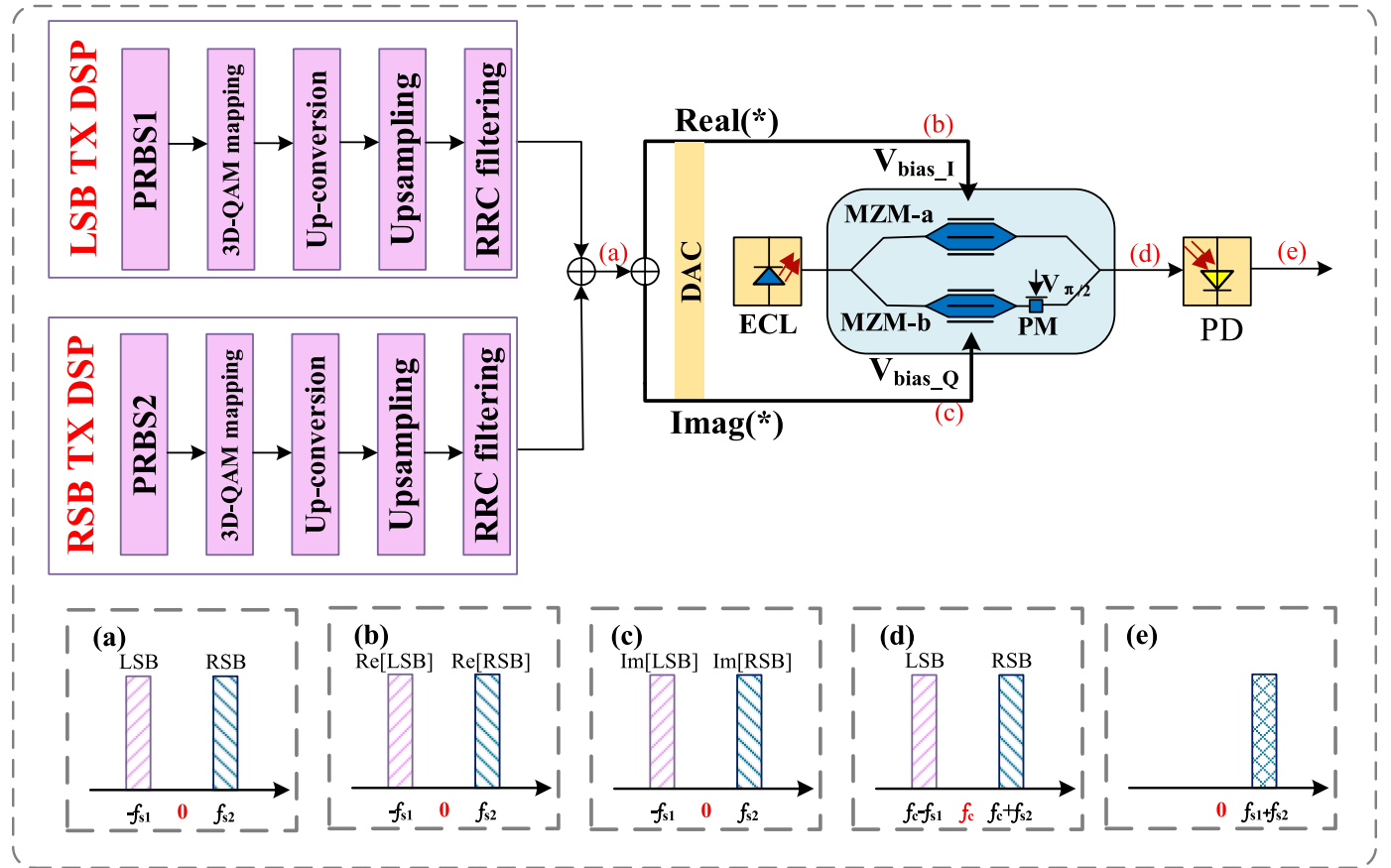


Fig. 2. Schematic diagram of generating three-dimensional signals through independent dual SSB transmission synthesis. (a) Spectrum diagram after sideband signal superposition, (b) real part spectrum diagram of dual SSB signal, (c) imaginary part spectrum diagram of dual SSB signal, (d) spectrum diagram of dual SSB signal after I/Q modulator, (e) spectrum diagram of received electrical signal after PD. PRBS: pseudo-random binary sequence, RRC: rising cosine, ECL: external cavity laser, MZM: Mach Zehnder modulator, PM: phase modulator, PD: photodiode.

$$\int_a^b \psi_1(x) \psi_3(x) dx = \int_a^b \sin(x) * \sin(x) * \cos(x) dx = \int_a^b \sin(x) * \sin(x) d(\sin(x)) = \frac{1}{3} \sin^3(x) \Big|_a^b \quad (9)$$

$$\int_a^b \psi_2(x) \psi_3(x) dx = \int_a^b \cos(x) * \sin(x) * \cos(x) dx = -\frac{1}{3} \cos^3(x) \Big|_a^b \quad (10)$$

If $b - a = 2\pi$, regardless of the values of a and b , then $\sin^2(b) - \sin^2(a) = 0$, but $\sin^3(b) - \sin^3(a) \neq 0$, $\cos^3(b) - \cos^3(a) \neq 0$. So, equation (8) is 0, and the two functions $\sin(x)$ and $\cos(x)$ are orthogonal to each other; Equations (9) and (10) are not 0, and the functions $\sin(x)$, $\cos(x)$, and $\sin(x) * \cos(x)$ are not orthogonal. That is to say, the functions $\sin(x)$, $\cos(x)$, and $\sin(x) * \cos(x)$ are not orthogonal to each other. It is worth noting that the superposition of non-orthogonal signals can indeed worsen signal crosstalk to a certain extent. Sideband signals of different frequencies will generate unwanted sideband signals after the PD interbeat, which will cause crosstalk with the expected sideband signals. In this case, it is necessary to adjust the sideband frequency interval to eliminate crosstalk, so that the interval between the unwanted sideband signal generated by the PD interbeat and the desired sideband signal is larger, and the effect of crosstalk is reduced. If the three vector amplitudes of the three-dimensional signal are different, the amplitude and power of the two sideband signals at the transmitting end

can be adjusted to make the sidebands after PD conversion basically at the same amplitude, ensuring that the amplitude of each vector signal of the three-dimensional signal is consistent, thereby reducing crosstalk. In addition, by optimizing the DSP algorithm at the receiving end, such as optimizing filter performance, improving CMMA equalization algorithm and dispersion compensation algorithm, etc., signal crosstalk can be further reduced. The simulation results in Section 3 indicate that the signal error rate is below the 7 % HD-FEC threshold of 3.8×10^{-3} . If we want to further reduce crosstalk, we can consider applying multiple input multiple output (MIMO) technology in the system in the future, using spatial diversity to reduce interference between signals, or using precoding technology at the transmitting end to preprocess signals and reduce crosstalk at the receiving end.

In the modulation and demodulation process of QAM and TDAM, the modulation function only functions with the received signal during demodulation, which is only multiplication, not integration. Therefore, the orthogonality of the modulation carrier function should have no impact on the demodulation process, which also explains why $\cos(x) * \sin(x)$ is selected as the modulation function and can still facilitate the completion of the demodulation process. It should be pointed out that although the three carrier functions $\sin(x)$, $\cos(x)$, and $\sin(x) * \cos(x)$ are not orthogonal, the mapping constellation during the modulation

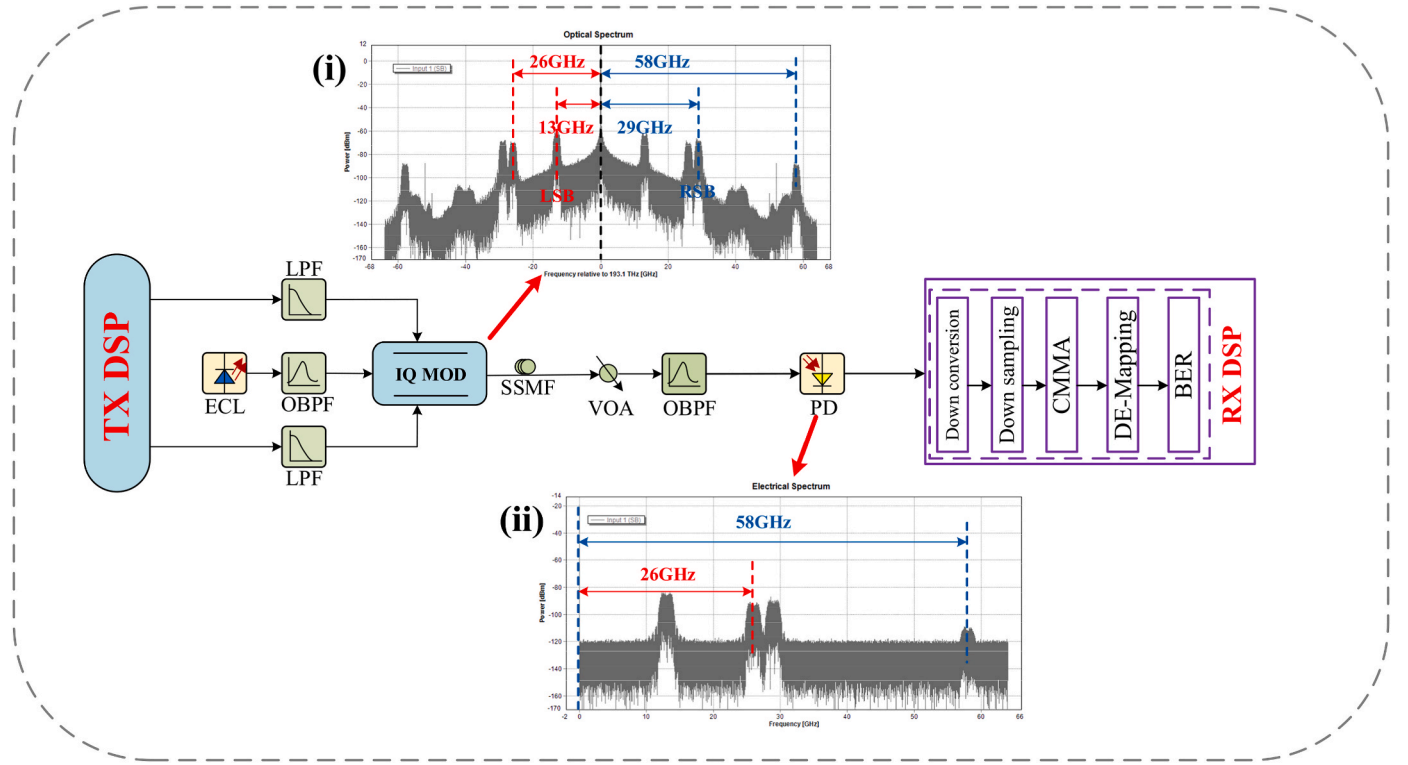


Fig. 3. System simulation setup diagram based on single PD receiving independent dual SSB signals. (i) The frequency spectrum of the dual SSB signal after passing through the I/Q modulator; (ii) Spectrum diagram of electrical signals received after PD, TX: transmitting sideband, OBPF: optical bandpass filter, LPF: low pass filter, SSF: standard single-mode fiber, VOA: variable optical attenuator, RX: receiving sideband, CMMA: cascaded multi-modulus algorithm.

process can be represented by an orthogonal stereo constellation diagram. That is to say, TDAM can also complete the modulation and demodulation process using three-dimensional constellation mapping and inverse mapping, which is simple and convenient without any difference from two-dimensional QAM.

The principle setup of the proposed scheme is shown in Fig. 2. At the transmitting end, two independent bit sequences are generated by a random number generator, one of which is mapped to RSB through regular 8QAM modulation. Another sequence is mapped to LSB using the same mapping method but with half amplitude modulation. Filter the two baseband signals using a 0.2 roll down raised root cosine (RRC) filter, followed by 2x oversampling. Next, the baseband signals are up converted to the desired LSB and RSB frequency bands at -13 GHz and

$+29$ GHz, respectively. The LSB and RSB signals are represented as:

$$E_L(t) = E_{LSB}(t)\exp(-j2\pi f_{s1}t) \quad (11)$$

$$E_R(t) = E_{RSB}(t)\exp(-j2\pi f_{s2}t) \quad (12)$$

Among them, f_{s1} and f_{s2} represent the carrier frequencies of LSB and RSB signals, E_{LSB} and E_{RSB} represent the RRC shaped LSB-8QAM and RSB-8QAM vector signals, respectively. These two signals are added to obtain an independent dual-SSB signal, as shown in Fig. 2(a).

The sum of LSB and RSB signals is sent to a digital to analog converter (DAC), and the DAC output can be represented as:

$$E(t) = E_L(t) + E_R(t) = E_{LSB}(t)\exp(-j2\pi f_{s1}t) + E_{RSB}(t)\exp(-j2\pi f_{s2}t)$$

$$= A_l \cos(-\omega_l t + \varphi_l) + A_r \cos(-\omega_r t + \varphi_r) + jA_l \sin(-\omega_l t + \varphi_l) + jA_r \sin(-\omega_r t + \varphi_r) \quad (13)$$

Table 1

The key parameters in system simulation.

Parameters	Values
DAC sampling rate	128 Gsa/s
ECL average power	-13 dBm
ECL linewidth	100 kHz
Vpi DC	2.5 V
Attenuation coefficient	0.2 dB/km
Dispersion	16 ps/nm/km
Nonlinear Index	2.6 p.m. ² /uW
PD thermal noise	10 pA/Hz ^{0.5}
PD bandwidth	30 GHz

Among them, A_l and A_r respectively represent the amplitude of RSB and LSB signals, φ_l and φ_r represent their phases, ω_l and ω_r represent their angular frequencies. The continuous wave (CW) optical signal with a frequency of f_c and an angular frequency of ω_c emitted from an external cavity laser (ECL) can be expressed as:

$$E_{CW}(t) = E_{CW} \exp(j2\pi f_c t) = E_{CW} \exp(j\omega_c t) \quad (14)$$

The continuous wave optical signal is sent to the optical input port of the I/Q modulator. The I/Q modulator consists of two optocouplers, two Mach Zehnder modulators (MZMs), and one phase modulator (PM). As shown in Fig. 2, the optocoupler of the I/Q modulator divides the input

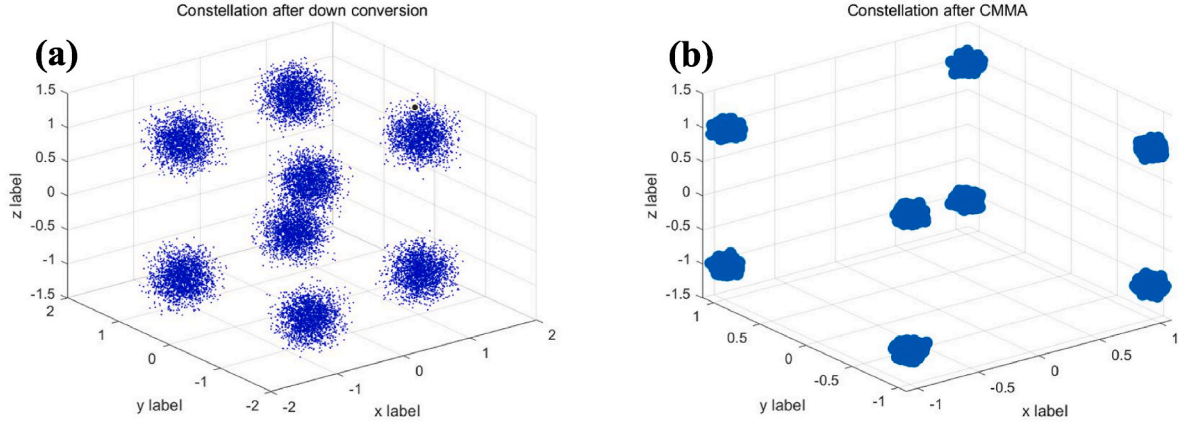


Fig. 4. Constellation of 2Gbaud 8TDAM vector signal under BTB transmission (a) Constellation after down conversion (b) Constellation after CMMA.

optical signal of the I/Q modulator into two branches with the same power. The upper branch MZM and lower branch MZM of the I/Q modulator are driven by the real and imaginary parts of the DAC output, respectively. The phase modulator of the I/Q modulator ensures that the I and Q branches of the I/Q modulator maintain a 90° phase difference. In our scheme, the I/Q modulator operates at the minimum transfer point (MITP).

Fig. 2(d) is a schematic diagram of the frequency spectrum of the I/Q modulator, from which we could see that at the output of the I/Q modulator, two independent vector signals of LSB and RSB are generated, and the frequencies are $f_c - f_{s1}$ and $f_c + f_{s2}$ respectively. Fig. 2(b) and (c) show the schematic diagrams of the frequency spectrum of signals passing through I and Q paths respectively, that is, the real part signal and imaginary part signal extracted from the superimposed independent dual SSB signal. After passing through the I/Q modulator, the signal is represented as:

$$E_{I/Q}(t) = E_{CW}(t)[J_{-1}(\alpha A_I)\exp(-j\omega_I t + j\varphi_I) + J_1(\beta A_r)\exp(-j\omega_r t + j\varphi_r)] \quad (15)$$

Among them, $J_{-1}(\cdot)$ and $J_1(\cdot)$ are the first type of Bessel function, α and β are the modulation coefficients of the I/Q modulator at operating

frequencies f_{s1} and f_{s2} , respectively. A_I and A_r are the amplitudes of the left and right sideband signals, respectively. The optical signal generated by modulation based on I/Q modulator is first transmitted through SSF, and the received optical signal is directly sent to the low-bandwidth PD at the receiving end for photoelectric conversion. The spectrum of the obtained electrical signal is shown in Fig. 2(e), while the LSB and RSB signals beat with the virtual carrier respectively after PD, and the high-order terms of the signal generated by beating the PD will be filtered out. The generated signal is shown as follows:

$$i_{RF}(t) = RJ_{-1}(\alpha A_I)J_1(\beta A_r)\cos[(\omega_I + \omega_r)t + (\varphi_I(t) + \varphi_r(t))] \quad (16)$$

Among them, R is the photoelectric conversion efficiency. From formula 16, it can be observed that the angular frequency $(\omega_I + \omega_r)$ of the received signal is the sum of the angular frequencies of the LSB and RSB signals, the phase $(\varphi_I + \varphi_r)$ is the sum of the phases of the LSB and RSB signals, and the signal amplitude is $J_{-1}(\alpha A_I)J_1(\beta A_r)$, which is the product of the two Bessel functions of the first type. The subsequent DSP algorithm is used to recover 3D-8QAM signals, separate LSB and RSB signals, and calculate the corresponding error rate of the signals.

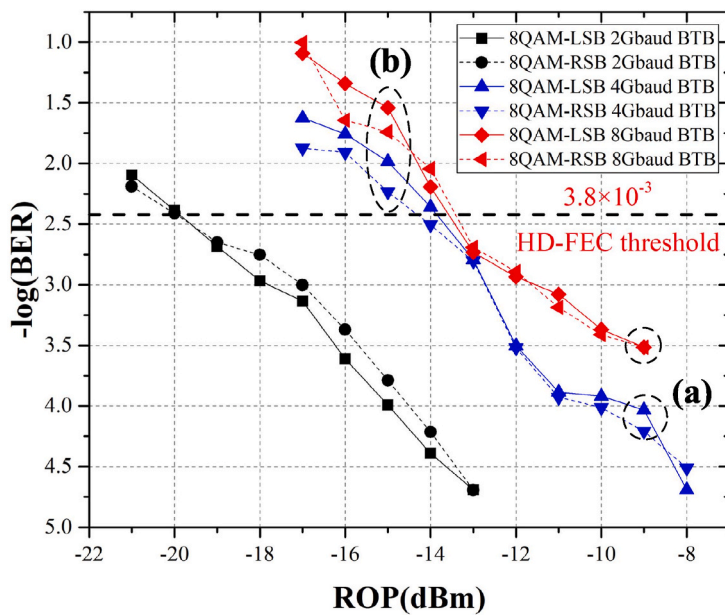


Fig. 5. The relationship between BER and ROP at different baud rates under BTB transmission. (a) Constellation diagram when ROP is -9 dBm; (b) Constellation diagram when ROP is -15 dBm.

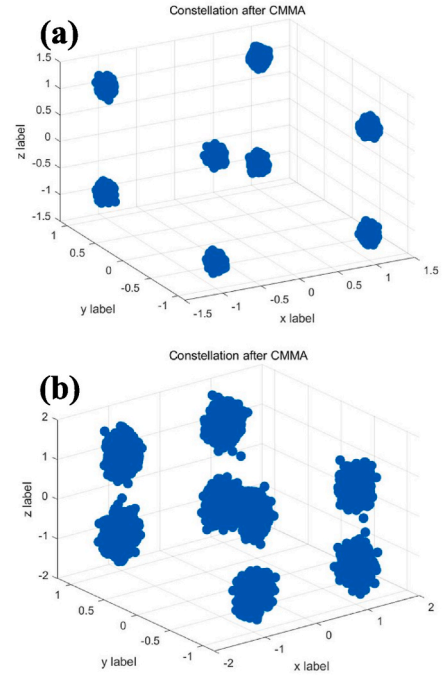
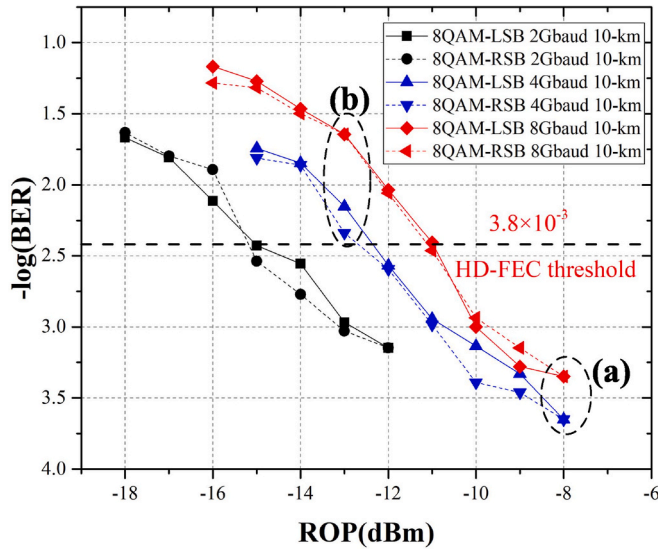


Fig. 6. The relationship between BER and ROP at different baud rates under 10 km SSMF transmission. (a) Constellation diagram when ROP is -8 dBm; (b) Constellation diagram when ROP is -13 dBm.

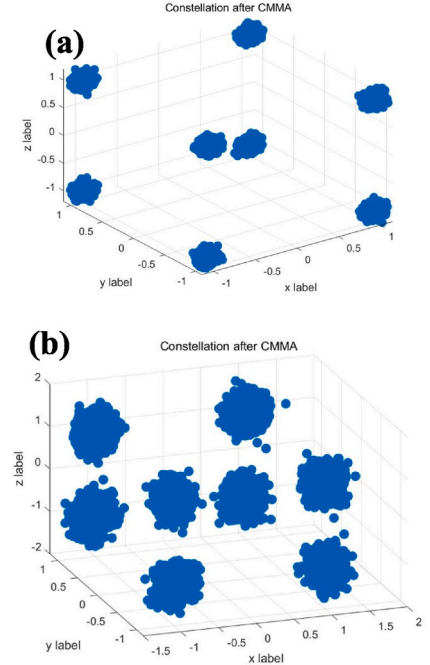
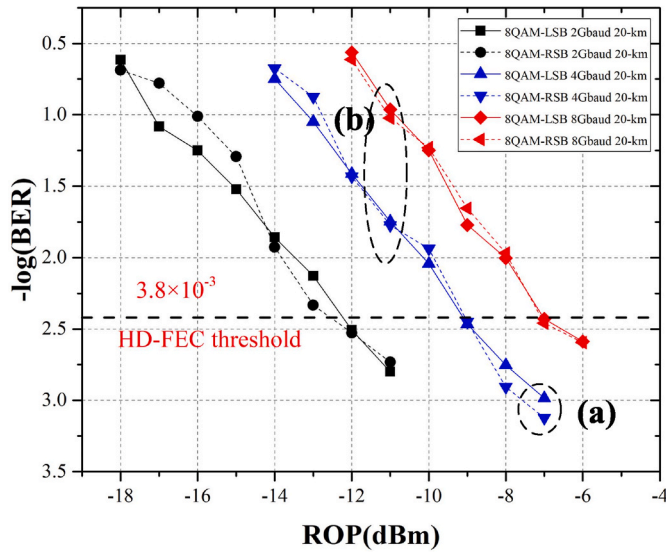


Fig. 7. The relationship between BER and ROP at different baud rates under 20 km SSMF transmission. (a) Constellation diagram when ROP is -7 dBm; (b) Constellation diagram when ROP is -11 dBm.

3. Simulation setup and results

To verify the feasibility and effectiveness of the proposed scheme, a system simulation based on IQ modulation was conducted. The experimental simulation schematic is shown in Fig. 3, and the key parameters in the simulation settings are shown in Table 1. The length of the two pseudo-random binary sequences generated by the offline end is 2^{14} . One is modulated by 3D-8QAM at -13 GHz, and the other is modulated by 3D-8QAM at 29 GHz with half amplitude. At the transmission end,

the half wave voltage of both Mach Zehnder modulators is set to 2.5 V. An external cavity laser (ECL) with a linewidth less than 100 kHz generates a continuous wave (CW) light wave. The ECL operates at a frequency of 193.10 THz, with a CW wavelength of 1548.705 nm (C-band) and an output optical power of -13 dBm. The signal formed by the superposition of the left and right bands, whose I and Q signal components are amplified by an electrical amplifier (EA) and used to drive the continuous light waves generated by ECL, produces a three-dimensional signal spectrum as shown in Fig. 3 (i). The measured I/Q modulator

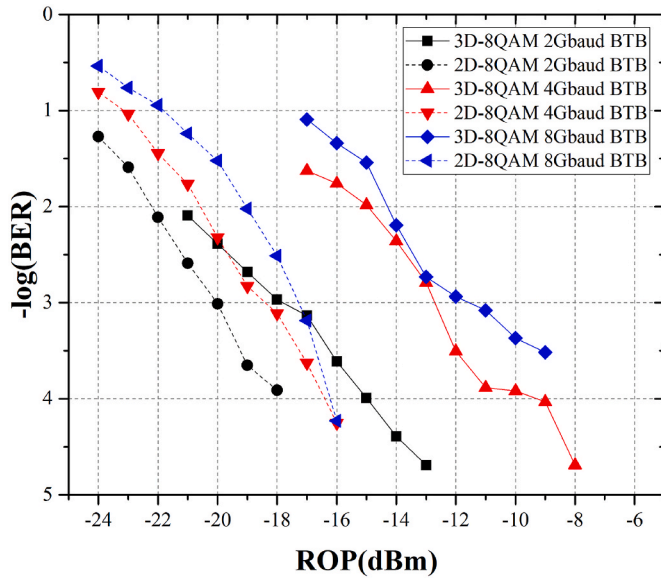


Fig. 8. The BER relationship between 3D-8QAM and 2D-8QAM at different baud rates under BTB transmission.

output signal spectrum is shown in Fig. 3 (i), with frequency intervals of 13 GHz and 29 GHz between LSB and RSB and the center carrier, respectively. After carrier suppression modulation, the central optical carrier is compressed to a very low level.

It is worth noting that we have chosen two specific frequencies, -13 GHz and 29 GHz, as the two sideband frequencies. This was not decided arbitrarily. Due to the square law effect of PD, two independent dual sideband signals at the transmitting end will appear on the spectrum of the receiving end after passing through PD, with two signals with frequencies twice the original signal frequency. If the traditional rule of using the same frequency for the left and right bands is adopted when selecting frequencies, it will exacerbate signal crosstalk. After continuous debugging, we found that the frequency of -13 and $+29$ GHz can effectively prevent signal mixing and so that reduce the difficulty of demodulation. The adjustment of frequency values will to some extent affect communication performance. When the baud rate increases, the difference between the two carrier frequencies could be appropriately widened. For example, when the baud rate is 4 Gbaud, we found experimentally that -11 and $+29$ GHz are the most suitable carrier frequencies. However, it is worth noting that if the frequency interval between the signals on the left and right sides is too small, the frequency of the signal after PD square law conversion will be smaller, and the signal will be greatly damaged after filtering by a filter in the later stage. If the frequency interval between the signals on the left and right sides is too large, due to the limited bandwidth of the IQ modulator and PD, it will have a significant impact on high-frequency signals and lead to performance degradation.

Next, after the signal passes through the fiber channel, we use an erbium-doped fiber amplifier (EDFA) to amplify the signal. At the receiving end, a variable optical attenuator (VOA) is used to adjust the received optical power (ROF). Before the optical signal undergoes photoelectric conversion, an optical filter (OBPF) is required to limit the bandwidth of the incoming PD signal to ensure the validity of the experimental results. Fig. 3 (ii) shows the electrical signal spectrum after PD square law detection characteristics and the received signal frequency will be located at 26 GHz and 58 GHz. After photoelectric conversion, the electrical signal is processed by an offline program for digital signal processing (DSP). Firstly, it is down converted to an intermediate frequency through heterodyne coherent reception. Then, the intermediate frequency signal is further processed by DSP, including down conversion, down sampling, cascaded multi-mode equalization

[22], and finally, the raw signal data is demodulated and mapped out. Each signal is separated to calculate the corresponding error rate. The corresponding constellation diagram of the processing flow is shown in Fig. 4.

Using the above simulation settings, we studied the transmission performance of the system at different transmission distances and baud rates, and evaluated the feasibility of the proposed scheme according to its error performance. The experimental results are shown in Figs. 5–7, showing the relationship between the bit error of LSB and RSB signals and the received optical power (ROP) at 2 Gbaud, 4 Gbaud and 8 Gbaud baud rates at different transmission distances.

In the simulation experiment, one carrier frequency was set to -13 GHz and the other carrier frequency was set to 29 GHz, respectively, to verify the transmission of signals from LSB and RSB at 2 Gbaud, 4 Gbaud, and 8 Gbaud baud rates, as well as the performance of the system in back-to-back (BTB), 10 km, and 20 km SSF transmission.

Fig. 5 show the relationship between the bit error rate and ROP of LSB and RSB signals in BTB transmission at 2 G, 4 G, and 8 G baud rates, respectively. Obviously, in BTB transmission, when the corresponding ROP is greater than -20 , -14 , and -13.4 dBm, respectively, the error rates of two independent SSB signals (LSB and RSB) are both below the 7% HD-FEC threshold of 3.8×10^{-3} .

Fig. 6 show the bit error rate and ROP of LSB and RSB signals in 10 km SSF transmission at 2 G, 4 G, and 8 G baud rates. It can be observed that in a 10 km SSF transmission, when the corresponding ROP is greater than -15 , -12 , and -11 dBm, the error rates of 2 Gbaud, 4 Gbaud, and 8 Gbaud independent SSB signals (LSB and RSB) are all lower than the 7% HD-FEC threshold of 3.8×10^{-3} .

Fig. 7 depict the relationship between the bit error rate and ROP of LSB and RSB signals in 20 km SSF transmission at 2 G, 4 G, and 8 G baud rates, respectively. It can be seen that in a 20 km SSF transmission, when the ROP is greater than -12.5 , -9 , and -7 dBm, the error rate of signals independent of 2 Gbaud, 4 Gbaud, and 8 Gbaud can all reach the threshold of 7% HD-FEC of 3.8×10^{-3} . It can be seen that as the signal transmission rate increases, limited bandwidth resources will lead to a deterioration of system performance.

We also quantitatively compared the performance of the $3D$ modulation and demodulation scheme with traditional modulation in terms of bit error rate. Fig. 8 shows a comparison of error rate performance between $3D$ - $8QAM$ and $2D$ - $8QAM$. Due to the fact that the minimum Euclidean distance in the three-dimensional signal constellation diagram is greater than that in the two-dimensional MQAM under the same conditions, the error performance of the three-dimensional MQAM signal is improved compared to the two-dimensional MQAM signal. We have supplemented a comparison of the error performance of $3D$ - $8QAM$ signals and $2D$ - $8QAM$ signals under the same rate and conditions, and found that $3D$ - $8QAM$ has a significant performance improvement compared to $2D$ - $8QAM$.

As shown in Fig. 8, when the baud rate is 2 Gbaud, 4 Gbaud and 8 Gbaud respectively, the error rate performance of $3D$ - $8QAM$ signals has been significantly improved compared to $2D$ - $8QAM$ signals.

In conclusion, the experimental results provide valuable insights into the performance characteristics of the proposed scheme under different transmission conditions, emphasizing the impact of transmission rate, distance, sideband characteristics and other parameters on the system error performance. These observations emphasize the importance of optimizing transmission parameters for achieving reliable and effective short distance communication.

4. Conclusion

In this article, we propose a new three-dimensional amplitude modulation and demodulation technique for use in independent dual sideband systems. Compared with traditional three-dimensional signals, it only adds one modulation carrier function $\sin(\omega t)\cos(\omega t)$ to expand the information carrying capacity of the transmission signal, and does

not require the three-way modulation carrier functions to be orthogonal to each other, reducing system cost and algorithm complexity. This system generates two columns of random binary sequences using digital methods. One is modulated with 3D-8QAM at -13GHz , and the other is modulated with 3D-8QAM at 29GHz with half amplitude. Then, the three dimensions x , y , and z of the three-dimensional signal are modulated onto the carriers $\sin(\omega t)$, $\cos(\omega t)$ and $\sin(\omega t)\cos(\omega t)$, respectively. At the receiving end, a simple DSP algorithm is used to recover the original signal through demodulation and separation. The performance of the system was evaluated by simulating SSMF transmission at different distances. The simulation results show that the system can successfully achieve independent 8TDAM signal BTB, 10km and 20km SSMF transmission at 2Gbaud , 4Gbaud and 8Gbaud , with a bit error rate of 7% and an HD-FEC threshold of 3.8×10^{-3} . This demonstrates the feasibility and effectiveness of the plan. The results indicate that the system has added a carrier function to carry more information, improve transmission rate, and reduce bit error rate; In addition, compared with traditional 3D signals, it does not require the three-way modulation carrier functions to be orthogonal to each other, simplifying the system structure, reducing algorithm complexity, and making it easy to implement. It has broad application prospects in short-range high-capacity communication.

CRedit authorship contribution statement

Yilin Chen: Writing – review & editing, Writing – original draft. **Zheng Hu:** Conceptualization. **Jiabao Zhao:** Conceptualization. **Feihan Li:** Conceptualization. **Hangzhi Zhu:** Conceptualization. **Jiangnan Xiao:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- [1] Shlomo Ovadia, Chinlon Lin, Performance characteristics and applications of hybrid multichannel ANI-VSB/M-QAM video lightwave transmission systems, *J. Lightwave Technol.* 16 (7) (1998) 1171–1186.
- [2] John R. Carson, Notes on the theory of modulation, *IEEE Proceed Institute Radio Eng* 10 (1) (1922) 57–64.
- [3] J. Hou, P.H. Siegel, L.B. Milstein, H.D. Pfister, Capacity-approaching bandwidth-efficient coded modulation schemes based on low-density parity-checkcodes, *IEEE Trans. Inf. Theor.* 49 (9) (2003) 2141–2155+2322.
- [4] Emmanuel Le Taillandier de Gabory, Tatsuya Nakamura, Hidemi Noguchi, et al., Experimental demonstration of the improvement of system sensitivity using multiplestate trellis coded optical modulation with QPSK and 16QAM constellations, *Optical Fiber Communications Conference, OFC*, 2015.
- [5] H. Louchet, K. Kuzmin, A. Richter, Improved DSP algorithms for coherent16-QAM transmission, *European Conference on Optical Communication (ECOC)*, 2008, p. 1.
- [6] S. Benedetto, P. Poggiolini, Combined amplitude and polarisation shift keying optical coherent modulation, *Electron. Lett.* 26 (13) (1990) 918–919.
- [7] S. Benedetto, P. Poggiolini, Theory of polarization shift keying modulation, *IEEE Transac* 40 (4) (1992) 708–721.
- [8] S. Benedetto, P.T. Poggiolini, Multilevel polarization shift keying: optimum receiver structure and performance evaluation, *IEEE Trans. Commun.* 42 (2–4 pt 2) (1994) 1174–1186.
- [9] S. Benedetto, R. Gaudino, Direct detection of optical digital transmission based on polarization shift keying modulation, *IEEE J. Sel. Area. Commun.* 13 (3) (1995) 531–542.
- [10] Li Chao, Kuo Yonghong, Qam signal recognition based on fractal analysis of constellation maps, *Inf. Technol.* 29 (3) (2005) 23–25.
- [11] T.M.D. Turkmani, A.A. Arowojolu, P.A. Jefford, C.J. Kellen, An experimental evaluation of the performance of two branch space and polarization diversity scheme at 1800MHz , *IEEE Trans. Veh. Technol.* 44 (2) (1995) 318–326.
- [12] R.G. Vaughan, Polarization diversity in mobile communications, *IEEE Trans. Veh. Technol.* 39 (3) (1990) 177–186.
- [13] M.R. Andrews, P.P. Mita, R. Carvalho, Tripling the capacity of wireless communications using electromagnetic polarization, *Nature* 409 (6818) (2001) 316.
- [14] T. Sowlati, D. Rozenblit, R. Pulella, M. Damgaard, E. McCarthy, Koh Dongssoo, D. Ripley, F. Balteanu, I. Gheorghe, Quad-Band GSM/GPRS/EDGE polar loop transmitter, *IEEE J. Solid State Circ.* 39 (12) (2004) 2179–2189.
- [15] R.T. Compton Jr., The triple antenna: an adaptive array with full polarization flexibility, *IEEE Trans. Antenn. Propag.* 29 (6) (1981) 944–952.
- [16] B. Lindmark, M. Nilsson, On the available diversity gain from different dual-polarized antennas, *IEEE J. Sel. Area. Commun.* 19 (2) (2001) 287–294.
- [17] R. Maher, K. Croussore, M. Lauermann, R. Going, Constellation shaped 66 GbD DP-1024 QAM transceiver with 400 km transmission over standard SMF, *European Conf Optical Commun (ECOC)*, 2017, pp. 1–3. Th.PDPB2, 2017-September.
- [18] F. Buchali, F. Steiner, G. Böcherer, L. Schmalen, P. Schulte, Rate adaptation and reach increase by probabilistically shaped 64-QAM: an experimental demonstration, *J. Lightwave Technol.* 34 (7) (2016) 1599–1609.
- [19] M. Yankov, F.D. Ros, E.P. Silva, S. Forchhammer, K.J. Larsen, Constellation shaping for WDM systems using 256QAM/1024QAM with probabilistic optimization, *J. Lightwave Technol.* 34 (7) (2016) 1599–1609.
- [20] Jiangnan Xiao, Xingying Li, Zirang Zhang, Yuming Xu, Long Chen, Jianjun Yu, Tolerance of the frequency deviation of LO sources at a MIMO system, *Opt. Commun.* 354 (2015) 14–20.
- [21] Runzhe Fan, Jie Li, Zepeng Gong, Fan Shi, Ming Luo, Li Xiang, Investigation of laser phase noise tolerance in simplified coherent PON with subcarrier multiplexing, *Opt. Express* 32 (22) (2024) 39384–39393.
- [22] E. Le Taillandier de Gabory, T. Nakamura, H. Noguchi, W. Maeda and S. Fujita, “Experimental demonstration of the improvement of system sensitivity using multiple state trellis coded optical modulation with QPSK and 16QAM constellations,” *Optical Fiber Communications Conference and Exhibition, OFC* 2015, paper W3K3.