A novel orthogonal modulation format of D8PSK/ASK with differential bi-phase encoding and its application in a label switching optical network*

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The principle of a novel orthogonal modulation format of differential 8-level phase-shift keying amplitude-shift keying (D8PSK/ASK) with differential bi-phase encoding (DBC) is introduced. Based on it, an optical labeling scheme, in which the payload is 100 Gbit/s D8PSK signal and the label is 10 Gbit/s DBC-ASK signal, is proposed and simulated. The results are compared with other current schemes, and the effects of transmission range, modulation extinction ratio (ER) and received power on system performance are analyzed, respectively. The results show that the spectrum efficiency and bit error rate (BER) are improved greatly, and when the modulation ER is increased to 11 dB, the balanced performance between the payload and label is achieved.

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Recently, many orthogonal modulation schemes have been demonstrated, such as differential phase shift-keying (DPSK) payload with amplitude shift keying (ASK) label, and frequency shift-keying (FSK) payload with ASK label[1-4]. To some extent, the schemes enhance the spectrum efficiency, but fail to meet the demand, and owing to the low modulation extinction ratio (ER), system performance greatly reduces. The schemes of Manchester-coded(MC)-ASK/DPSK and FSK/MC-ASK are proposed to solve the problem of low ER[5-7], but their bit rates are limited, and compared with traditional optical label systems, there is no increase of spectrum efficiency. In Refs.[8-10], the scheme of differential quadrature phase shift-keying/inverse return to zero (DQPSK/IRZ) is demonstrated as a solution. However, the generation of IRZ signal is complex, and it's also difficult to determine synchronous clock in demodulation.

The spectral width of differential 8-level phase-shift keying (D8PSK) is narrower than DPSK at the same symbol rate, and its system capacity is much higher[11,12], but there is no report about it in optical label network. In addition, compared with IRZ system, the performance of ASK with differential bi-phase encoding (DBC) is much better[13,14]. It doesn't require strict time synchronization, the processes of modulation and demodulation are much simpler, and the decoding errors caused by polarity reversal can be solved effectively. Based on the above modulation formats, we propose a novel orthogonal modulation format of D8PSK/DBC-ASK in this paper, and it is demonstrated successfully in a label switching optical network.

The configuration of the proposed D8PSK/DBC-ASK transmitter is shown in Fig.1(a), and it consists of a D8PSK modulator and an optical DBC-ASK modulator.

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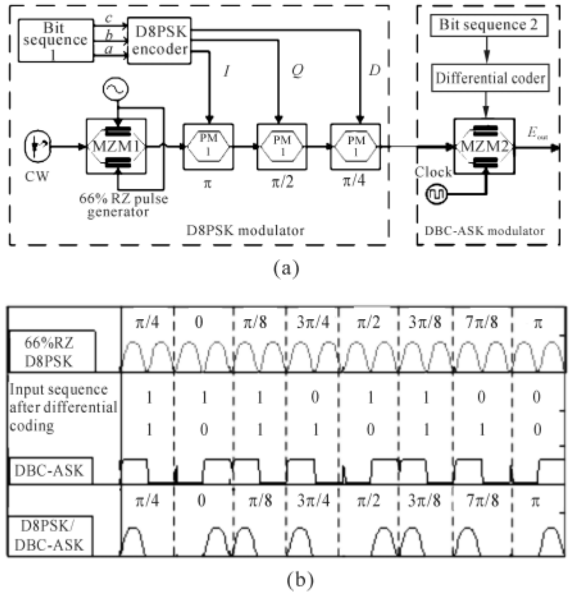


Fig.1 (a) Configuration of D8PSK/DBC-ASK transmitter; (b) Generation of the orthogonal signal in time domain

In D8PSK modulator, the encoder encodes three independent data of a, b and c, which are acquired from bit sequence 1 parallelly, into three differentially-encoded data sequences of I, Q and D, and the logical relationships between them are found to be

$$I_k = \overline{D_{k-1}Q_{k-1}}(I_{k-1}\oplus a)+(\overline{D_{k-1}}Q_{k-1}+D_{k-1}\bar{c})(I_{k-1}\oplus b)+D_{k-1}c(I_{k-1}\oplus Q_{k-1}\oplus a),$$
$$Q_k = D_{k-1}(c+Q_{k-1})+\overline{D_{k-1}}(Q_{k-1}\oplus a\oplus b),$$
$$D_k = a\oplus b\oplus c\oplus D_{k-1}, \quad (1)$$

where I_k, Q_k and D_k are output bits of the encoder for a given set of input bits of a, b and c, and I_{k-1}, Q_{k-1} and D_{k-1} are the predecessor bits of the current outputs I_k, Q_k and D_k.

The first Mach-Zehnder modulator (MZM1) is for RZ pulse carving. After that, the optical carrier can be modulated by three optical phase modulators (PMs) with respective phase shift of π, π/2 and π/4. The PMs are driven by the encoded bits I, Q and D respectively, thus each symbol carries three bits of information and the phase difference θ_i of optical carrier has 8 values, and then D8PSK modulation is accomplished. In time domain, the D8PSK signal can be described as

$$E_{\text{D8PSK}}=|E_0|\exp\mathrm{j}(\omega t+\varphi+\theta_i), \quad (2)$$

where $|E_0|$ is the amplitude of the optical carrier and it's a constant, ω is the angular frequency, φ is the original phase of the carrier, and $\theta_i=(i-1)\,\pi/8$, $i=1, 2, \ldots, 8$.

In DBC-ASK modulator, bit sequence 2 is coded by a differential coder, and the output is employed as driving signal for the upper arm of MZM2. The lower arm is driven by a clock, and its rate is two times higher than bit sequence 2. The modulation voltage of two arms is 5 V, and there is no bias. The D8PSK signal is loaded in optical input port of MZM2, and then bit information is carried on the amplitude of the carrier by DBC-ASK modulation. The generation process of the orthogonal signal in time domain is shown in Fig.1 (b). We can see that in each bit period, DBC-ASK signal has optical power, so high modulation ER has little influence on phase information. By Eq.(2), the orthogonal signal E_{out} can be inferred as

$$E_{\text{out}}=A(t)\,E_{\text{D8PSK}}=A(t)\,|E_0|\exp\mathrm{j}\,(\omega t+\varphi+\theta_i), \quad (3)$$

where $A(t)$ is the information of bit sequence 2, and there is no bias voltage on two arms of MZM2, so we can calculate

$$A(t)=10^{0.05\alpha}\,[\gamma \mathrm{e}^{\mathrm{j}\pi v_2(t)/v_{\pi\text{RF}}}+(1-\gamma)\,\mathrm{e}^{\mathrm{j}\pi v_1(t)/v_{\pi\text{RF}}}], \quad (4)$$

$$\gamma=\left(1-1/\sqrt{10^{ER/10}}\right)/2, \quad (5)$$

where α is the insertion loss of MZM2, $v_1(t)$ and $v_2(t)$ are the driving voltages of two arms, and $v_{\pi\text{RF}}$ is radio frequency (RF) switching voltage which is equal to 5 V.

The structure of D8PSK/DBC-ASK receiver is illustrated in Fig.2. The orthogonal signal is separated by a 3 dB coupler, and then two identical signals are sent to D8PSK demodulator and DBC-ASK demodulator, respectively.

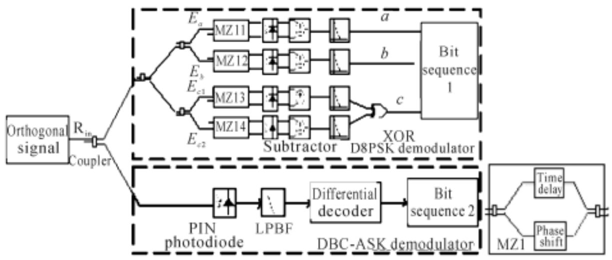


Fig.2 Schematic diagram of D8PSK/DBC-ASK receiver

Direct detection is employed in DBC-ASK demodulator which consists of a PIN photodiode, a low-pass Bessel filter (LPBF) and a differential decoder. Because the detected information is just the amplitude of the carrier, DBC-ASK signal can be demodulated correctly.

In D8PSK demodulator, the input is separated into four signals as E_a, E_b, E_{c1} and E_{c2} by two-stage couplers, and $E_a(t)$ in frequency domain can be described as

$$E_a=(R_{\text{in}}\quad 0)\boldsymbol{H}\begin{pmatrix}1&0\\0&0\end{pmatrix}\boldsymbol{H}\begin{pmatrix}0&1\\0&0\end{pmatrix}\boldsymbol{H}\begin{pmatrix}1\\0\end{pmatrix}, \quad (6)$$

where $\boldsymbol{H}$ is the transmission matrix of 3 dB coupler, and $\boldsymbol{H}=\begin{pmatrix}\sqrt{0.5}&\mathrm{j}\sqrt{0.5}\\\mathrm{j}\sqrt{0.5}&\sqrt{0.5}\end{pmatrix}$. R_{in} is input of the orthogonal signal receiver, and in back-to-back (B-T-B) system $R_{\text{in}}=E_{\text{out}}$. From Eqs.(3) and (6), in time domain, we can calculate that

$$E_a(t)=\frac{\sqrt{2}}{4}\,\mathrm{j}A(t)\,|E_0|\exp\mathrm{j}(\omega t+\varphi+\theta_i)\ . \tag{7}$$

In a similar way, $E_b(t)$, $E_{c1}(t)$ and $E_{c2}(t)$ can be received. Four parallel signals are respectively sent to four Mach-Zehnder interferometers, each of which has 3 bits delay, and between two arms of MZI there are the phase shifts of 3π/8, -π/8, π/8 and -3π/8 respectively. The process of signal $E_a(t)$ via MZI1 can be described as

$$\begin{pmatrix}E_{a1} & E_{a2}\end{pmatrix}=\begin{pmatrix}E_a & 0\end{pmatrix}\boldsymbol{H}\begin{pmatrix}\mathrm{e}^{-\mathrm{j}\omega\tau} & 0\\ 0 & \mathrm{e}^{\mathrm{j}3\pi/8}\end{pmatrix}\boldsymbol{H}\ , \tag{8}$$

where $\begin{pmatrix}\mathrm{e}^{-\mathrm{j}\omega\tau} & 0\\ 0 & \mathrm{e}^{\mathrm{j}3\pi/8}\end{pmatrix}$ is the transmission matrix of two arms of MZI1, and τ is time delay. E_{a1} and E_{a2} are outputs of MZI1, and their expressions can be inferred from Eq.(8) as

$$E_{a1}(t)=\frac{1}{2}A(t)\,|E_0|\,\mathrm{e}^{\mathrm{j}(\omega t+\varphi)}\left(\mathrm{e}^{\mathrm{j}\varphi_2}-\mathrm{e}^{\mathrm{j}\frac{3\pi}{8}+\mathrm{j}\varphi_1}\right)\ ,$$

$$E_{a2}(t)=\frac{1}{2}\mathrm{j}A(t)\,|E_0|\,\mathrm{e}^{\mathrm{j}(\omega t+\varphi)}\left(\mathrm{e}^{\mathrm{j}\varphi_2}+\mathrm{e}^{\mathrm{j}\frac{3\pi}{8}+\mathrm{j}\varphi_1}\right)\ , \tag{9}$$

where φ_1 is the phase of $E_{in}(t)$, and φ_2 is the phase of $E_{in}(t-\tau)$.

Then E_{a1} and E_{a2} are converted into electrical signals which only include amplitude information by PIN photodiodes, and the expressions of electrical signals can be described as

$$I_{a1}=|E_{a1}(t)|\ ,\ I_{a2}=|E_{a2}(t)|\ . \tag{10}$$

The decision threshold is zero level. When the value of I_{a1}- I_{a2} is greater than decision threshold, the output is the determined as binary "1", and on the contrary, the output is binary "0". Thus, the decision output is the data *a*, which is one of the transmitter's inputs. In the same way, data *b* and *c* can be correctly demodulated, too.

In view of the excellent performance of the above modulation format, a novel orthogonal optical labeling scheme is proposed, and the setup is shown in Fig.3.

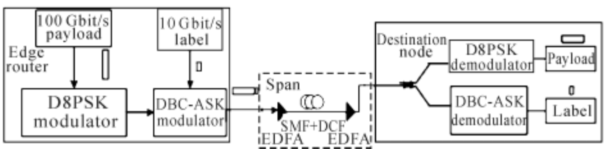


Fig.3 Setup for the D8PSK/DBC-ASK orthogonal optical labeling system

In edge router, $2^{11}-1$ payload and 2^7-1 label are generated by two PBRS generators, and the distrbuted feedback (DFB) laser works at central frequency of 193.1 THz with 0 dBm transmitted power. 100 Gbit/s payload information is carried on the carrier's phase by D8PSK modulation, and then the output is sent to DBC-ASK modulator, where the label is operated at 10 Gbit/s with NRZ format and a 20 Gbit/s clock signal is added on the lower arm of MZM2 with ER of 11 dB. At last, the D8PSK payload combined with DBC-ASK label is received. The carrier's phases before and after orthogonal modulation are shown in Fig.4. It can be seen that there is little phase damage for orthogonal signal with high ER. It's because DBC-ASK signal is not sensitive to modulation ER, and it always has optical power in each period of bit "1" or "0", which makes the information loaded in other parameters can be reserved effectively.

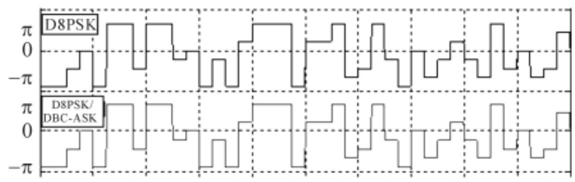


Fig.4 Phases of D8PSK signal and orthogonal signal

In Fig.5, we can see that in 100 Gbit/s optical transmission system with single channel, since each symbol contains 3 bits, main lobe width of D8PSK/DBC-ASK signal is narrower. Therefore, its spectrum efficiency and system capacity are much higher, and undoubtedly it's an ideal solution for growing demand of bandwidth.

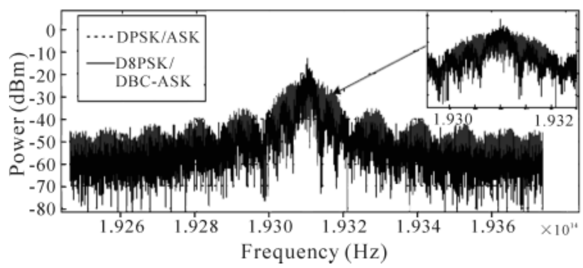


Fig.5 Spectra of D8PSK/DBC-ASK signal and DPSK/ASK signal

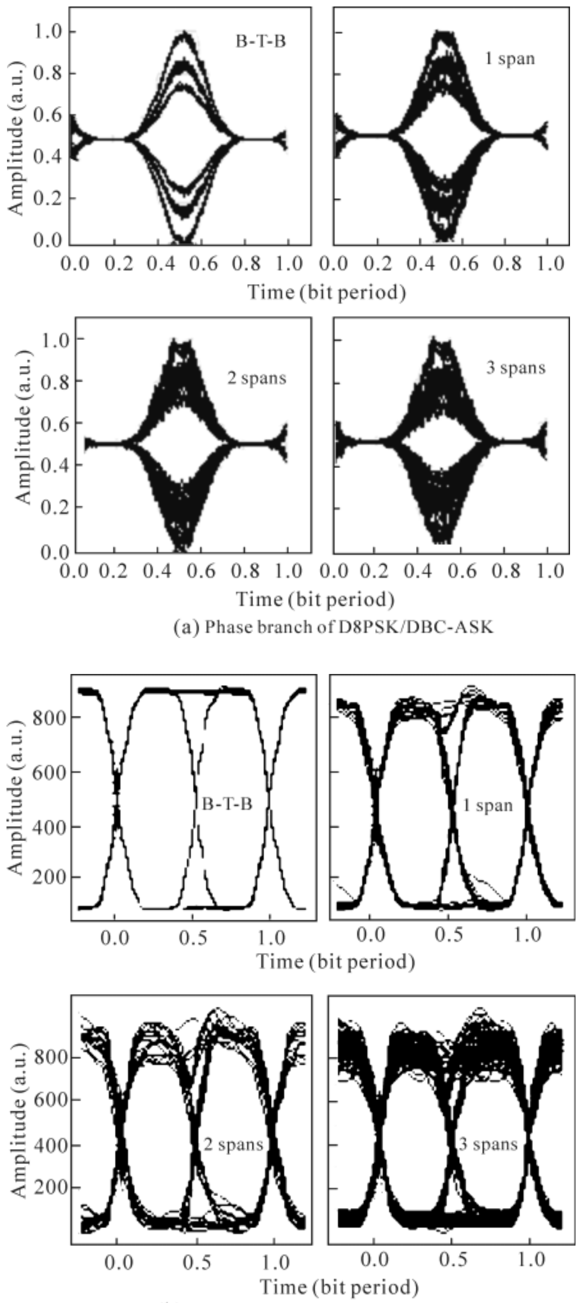
The transmission link is composed of some spans, which include erbium doped fiber amplifier (EDFA), single mode fiber (SMF) and dispersion compensation fiber (DCF). The length of each span is 100 km, and the fiber's parameter setting is shown in Tab.1.

Tab.1 Fiber parameters

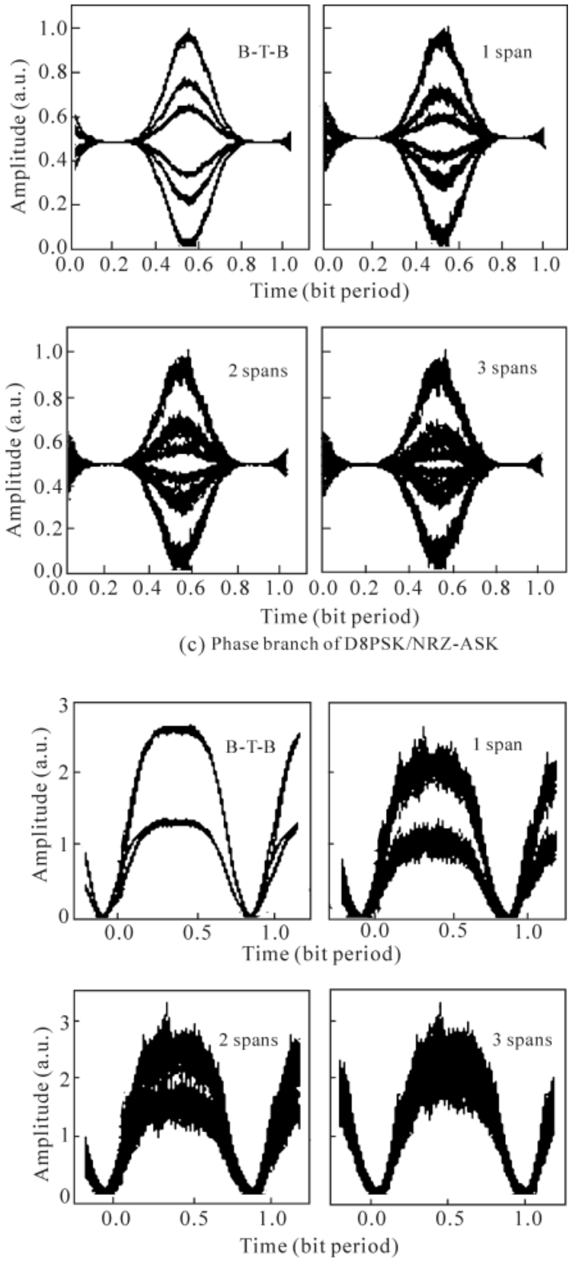
Fiber type	α(dB/km)	D(ps·nm^{-1}·km^{-1})	A_{eff}(μm^2)	Dispersion slope (ps·nm^{-2}·km^{-1})
SMF	0.2	17	70	0.075
DCF	0.5	-85	22	-0.300

The transmission performance of D8PSK/DBC-ASK signal is analyzed in destination node. As a comparison, D8PSK/NRZ-ASK signal which is transmitted with 4 dB modulation

ER in the same link is analyzed, too. From Fig.6(a) and (b), we know that as the power of the orthogonal signal is balanced, the phase branch is less affected by nonlinear effects. In amplitude branch, sensitivity of the receiver is enhanced due to the large modulation ER, and as the amplitude information is differentially coded, there are much fewer errors in demodulation, so the performance of D8PSK/DBC-ASK signal after 3 spans transmission is well, and the BER of both payload and label can reach better than 10^{-6}. In Fig.6(c) and (d), it can be seen that the performance of D8PSK/NRZ-ASK signal is much worse in the same link, and the signal after 3 spans transmission is overwhelmed by the noise, which can't be demodulated correctly.



(a) Phase branch of D8PSK/DBC-ASK
(b) Amplitude branch of D8PSK/DBC-ASK



(c) Phase branch of D8PSK/NRZ-ASK
(d) Amplitude branch of D8PSK/NRZ-ASK

Fig.6 Eye diagrams of D8PSK/DBC-ASK signal and D8PSK/NRZ-ASK signal

In Fig.7, the impact of ER on BER in three kinds of orthogonal systems is illustrated. We can see that the payload BER is enhanced with the increase of ER, while the label BER is reduced, but the variation trends of three kinds of labels BER are similar, and the payload with NRZ-ASK label is influenced more easily than other payloads by ER. In addition, there is a balance of modulation ER between the label and payload performance in D8PSK/NRZ-ASK system. It appears to be 4 dB which makes both label and payload BERs be around 10^{-6}, and the optimum ER can be increased to 9 dB with IRZ label or 11 dB with DBC label. Thus, in the case of high modulation ER, the performance of D8PSK/DBC-ASK is better than others, and the BERs of both detected payload and label signals can meet respective demand of the receiver and reach 10^{-12} without transmission.

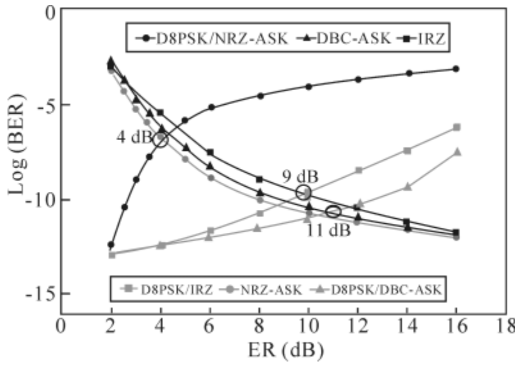


Fig.7 BER versus ER in three kinds of orthogonal systems

The BER performance of the payload and label against the received power is shown in Fig.8. There are four orthogonal signals with optimum ER in Fig.8. It can be seen that all labels are sensitive to the received power. In the range of 2 dBm the performance deteriorates soon, but compared with DBC label and NRZ label, there is an increase of BER with two orders of magnitude for the former. Among payloads, the performance of payload with DBC label is better than others. As the bi-phase coding (BC) label without differential encoding, there is a small gap from payload with DBC label.

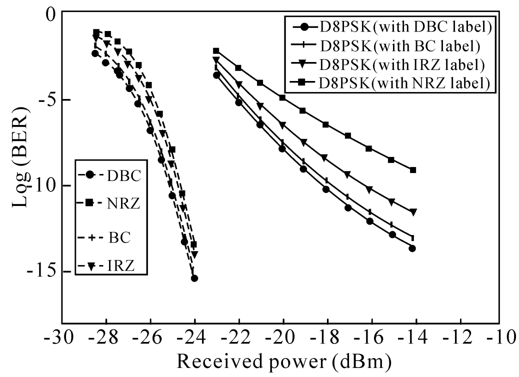


Fig.8 BER versus received power

In this paper, a novel optical labeling scheme is proposed and demonstrated. The results show that system capacity and spectrum efficiency contrasted with traditional optical labeling systems are enhanced availably. Compared with D8PSK/NRZ-ASK system, the modulation ER is increased to 11 dB, which makes the amplitude receiver more sensitive but without deterioration of payload. In addition, with the same received power, its BER is lower than the system with IRZ label by two orders of magnitude. Therefore, the proposed scheme, which increases both bit rate and system performance, can be an effective design for the large-capacity and high-rate optical label switching network.

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