Study of FSK/IM orthogonal modulation system with optical Manchester-coded payload

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We study the performance of an orthogonal modulation system with frequency-shift keying (FSK) label and optical Manchester-coded (MC) payload. Simulation result shows that by introducing an optical MC payload, the available extinction ratio (ER) value of a FSK and intensity modulation (IM) orthogonal modulation system can be improved from 5 to 9 dB for system optimization, exhibiting great advantages over the traditional non-return-to-zero (NRZ) payload. Besides, the bit error rate (BER) characteristics of both label and payload show a more remarkable advantage than that of NRZ coding, verifying itself as a perfect candidate for the payload coding method in orthogonal modulation systems.

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In recent years, optical burst switching (OBS)[1] and optical label switching (OLS)[2] technologies have been studied as promising solutions for optical packet switching (OPS). In OLS networks, the low-bit-rate optical label contains routing information and propagates together with data payload. At each intermediate node, the OLS router can transparently forward the payload information directly in the optical layer based on the label information, which avoids the costly optical-electrical-optical (OEO) conversion of the high-speed data.

Several labeling methods have been proposed and demonstrated as possible solutions[3]. Among them, an orthogonal modulation method named optical frequency-shift keying/intensity modulation (FSK/IM) has been regarded as a feasible scheme due to its compact spectrum, simple label swapping, and remarkable scalability to high bit rates[4−8]. However, in FSK/IM systems FSK label introduces crosstalk to the intensity modulated payload, thus limiting the scalability of the labeling scheme and reducing the system modulation performance[5−7]. Manchester coding, also referred to as bi-phase coding, has been experimentally demonstrated to reduce such crosstalk[9,10], for which the data signal is electrically encoded by an encoder before adding it to the optical carrier by intensity modulator.

Recently, a novel method has been proposed for the direct generation of Manchester encoded optical signal, through a dual-drive Mach-Zehnder modulator (DD-MZM)[11]. In this case no extra encoder is needed, which simplifies the system and reduces the total cost. However, the optical Manchester-coded (MC) signal has not yet been used as high-speed payload in OLS systems. In this letter, we discuss the feasibility of introducing optical Manchester coding in a FSK/IM orthogonal modulation system, achieving FSK label with optically encoded Manchester payload. Simulation results prove that by adjusting the modulation voltage of DD-MZM, a good trade-off between label and payload performances can be achieved at high extinction ratio (ER), without much bit error rate (BER) penalty of payload or label.

Optical Manchester coding can be obtained by driving the two arms of a DD-MZM with electrical non-return-to-zero (NRZ) data and an electrical clock signal, respectively, and adjusting the modulation voltage appropriately to make an exclusive OR (XOR) operation between the NRZ and clock signals[11]. The principle of Manchester coding is to use either rise or fall of the signal in the middle of each bit period 'T' to represent '0' or '1', as shown in Fig. 1.

Manchester (split phase) coding has been widely studied in optical and electrical communication systems due to some of its intrinsic characteristics.

1) Compared with the usual NRZ code, its main advantages are easy timing extraction, zero direct current (DC) content, and no laser pattern dependency. The laser pattern dependency is caused by the possible long strings of '1's or '0's and degrades the receiver sensitivity through variations in laser power of '1' level[12].

2) Manchester coding greatly suppresses the crosstalk in subcarrier multiplexing (SCM) signaling[13] and the spectrum overlapping between label and payload in the FSK/IM orthogonal modulation scheme[10] through spectrum shaping.

Also, proper decoding methods of MC signal have been proposed to improve the system performance.

1) A weighted processing of the two bit halves of Manchester data brings a large BER improvement for the data corrupted by multiplicative noise (signal-dependent

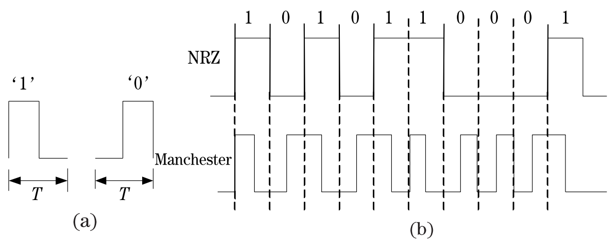

Fig. 1. (a) Manchester coding; (b) Manchester and NRZ.

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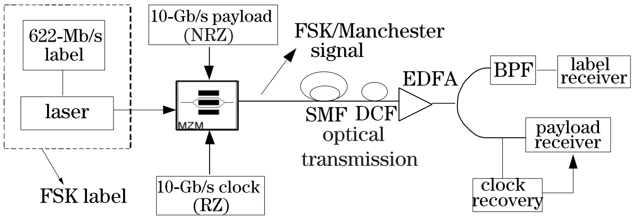

Fig. 2. FSK/IM scheme with optical MC payload.

noise)[14], which is introduced by several important communication devices such as avalanche photodiode (APD) and optically amplified detectors.

2) The novel decoding method which uses differential receiver and synchronous decoder can handle the fast power fluctuations and large coherent crosstalk without doubling the bandwidth requirement compared with NRZ code[15].

In order to discuss the performance of FSK/IM system with optical MC payload, we establish a simulation setup as shown in Fig. 2, where 2^7–1 label and 2^{23}–1 payload are generated by two Pseudo random bit sequence (PRBS) generators. The 622-Mb/s FSK label is first obtained by direct modulation of a distribute feedback (DFB) laser with 20-GHz frequency deviation and 10-MHz linewidth at the central frequency of 193.1 THz, then sent to a DD-MZM where the payload information operating at 10 Gb/s with NRZ format and a 10-Gb/s return-to-zero (RZ) clock signal are added on the two arms, respectively. Then the FSK label signal combined with optical MC payload is obtained and sent to fiber transmission link which consists of 100-km single-mode fiber (SMF) and 20-km dispersion compensation fiber (DCF). The attenuation coefficients of the SMF and DCF are 0.2 and 0.3 dB/km, respectively, and the corresponding dispersion coefficients are 16 and –80 ps/(nm·km) with dispersion slope of 0.08 and –0.28 ps/(nm^2·km), respectively. An Er-doped fiber amplifier (EDFA) is used before optical receiver amplifies the transmitted signal, and the 3-dB bandwidth of the band pass filter (BPF) for FSK label detection is 10 GHz. In the payload receiver after positive-intrinsic-negative (PIN) photodiode, a mixer and a low-pass filter (LPF) detect the phase difference between the signal and a reference clock extracted from the clock recovery module. The phase comparison between the MC signal and the synchronized clock then reproduces its original logical bit.

In the system, the laser phase noise is modeled using the probability density function:

$$f(\Delta\phi) = \frac{1}{2\pi\sqrt{\Delta f \mathrm{d}t}} \cdot \mathrm{e}^{-\frac{\Delta\phi^2}{4\pi\Delta f \mathrm{d}t}}, \tag{1}$$

where $\Delta\phi$ is the phase difference between two successive time instants and $\mathrm{d}t$ is the time discretization. A Gaussian random variable for the phase difference between two successive time instants with zero mean and a variance equal to $2\pi\Delta f$ has been assumed, with Δf being the laser linewidth.

As for the EDFA before receivers, the noise center frequency is 193.4 THz, with 13-THz noise bandwidth and 125-GHz noise bins spacing. The noise threshold and noise dynamic (threshold ratio for adaptation of noise bins) for both the laser and the EDFA are –100 and 3 dB, respectively. At the receiver end, possible noise might be introduced by the photo detector in terms of amplified spontaneous emission (ASE) noise, thermal noise, and shot noise.

In Manchester coding, there is always at least one transition of '0' and '1' levels. Therefore the clock recovery is much easier than that for NRZ coding. On the other hand, Manchester coding actually doubles the transmitted bit rate compared with NRZ due to its 1B/2B coding nature which uses '10' to represent '1' and '01' to represent '0', so a wider bandwidth is required[12].

The upper figures in Figs. 3(a) and (b) are the optical spectra of FSK labeled signals with NRZ and optical MC payloads, respectively, and the lower figures show the details of the spectra. The '0' and '1' of label signal are represented by either of the two frequencies deviating from the central frequency, forming FSK-labeling with two peaks shown in Fig. 3(a). At the same time, the high-speed payload is intensity-modulated on the FSK label signal and thus building up the FSK/IM orthogonal modulation. The intensity ripples introduced by IM thereby affect the FSK label, as shown in Fig. 3, taking the 193.09-THz peak for example, since the same optical carrier is used for both modulation formats and a spectrum overlap happens. In the case of MC payload, as a DC-null is provided[16], the spectrum is re-shaped with the carrier component of IM suppressed, resulting in a symmetrical structure of intensity ripples which allows much more power to be centralized around

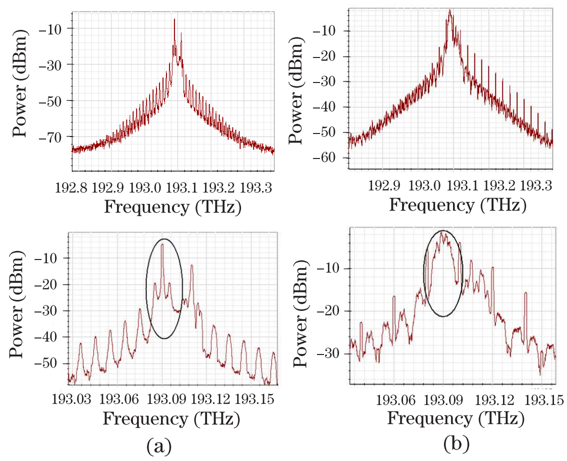

Fig. 3. Spectra of combined FSK/IM signal with NRZ label and (a) NRZ payload, (b) MC payload (resolution bandwidth 0.01 nm).

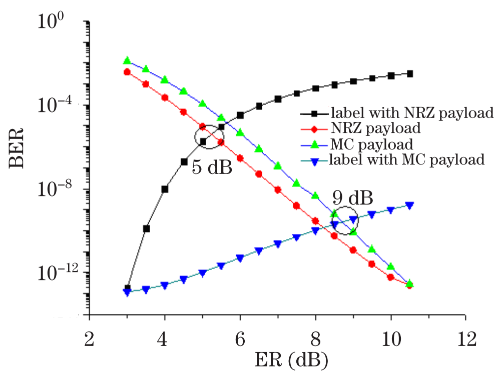

Fig. 4. BER versus ER in FSK/IM system with NRZ and MC payload.

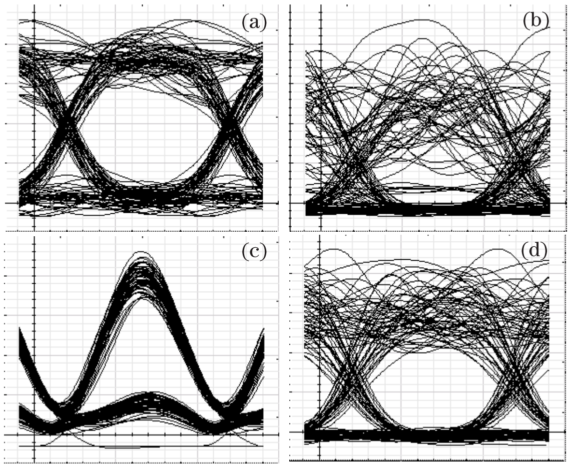

Fig. 5. Eye diagrams of label and payload in the presence of (a), (b) NRZ and (c), (d) Manchester. (a) payload; (b) label; (c) payload; (d) label. ER=10 dB.

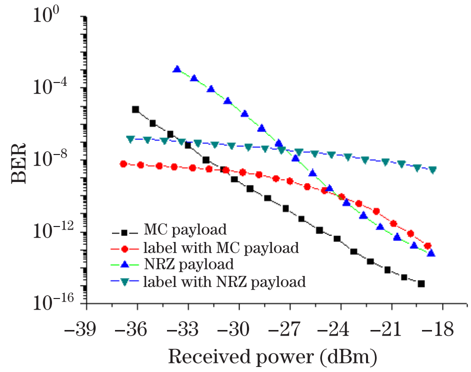

Fig. 6. BER versus received power.

the FSK-peaks and therefore more frequency component can pass the BPF during label detection. In this way, the interference from IM to FSK labeling can be greatly reduced.

In optical orthogonal modulation systems, a high ER is expected for the intensity modulated data transmission. However, a low ER value is preferred for the label, otherwise a possible long string of '0's will deteriorate the label detection. Therefore a compromised ER is needed, and the system performance is limited by this ER value.

Figure 4 illustrates the influence of ER upon system performance. It can be seen that the payload BER improves with the enhancement of ER, but the label BER degrades in both NRZ and Manchester coding cases. Therefore a trade-off between the label and payload performances exists, and appears to be a nearly 5-dB ER in the traditional NRZ coding case, with both label and payload BERs to be around 10^{-6}. With optical MC payload, the optimum ER can increase to 9 dB, resulting in a 10^{-10} BER for both label and payload. These results are based on the same received optical power adjusted for the comparison of two coding cases, in our simulation, which is –30 dBm for the payload and –36 dBm for the label.

In Fig. 4, it shows that Manchester coding causes some degradation of payload BER when the ER is lower than 10.5 dB. However, to judge the performance of an orthogonal modulation system, benefits of label and payload should be taken into consideration, which compares the two coding methods at their optimum points, namely the best-ER points. At these points, it is obvious to see the predominance of MC payload over NRZ payload. Besides, by introducing optical MC payload, the label BER becomes insensitive to ER increment, resulting in a remarkable improvement for label detection.

Figure 5 shows the eye diagrams of detected signal with NRZ and optical MC payloads. With an ER of 10 dB or higher, the MC payload and its label signal show a large eye opening. With NRZ coding, the label signal is greatly distorted and the eye can hardly open. This is mainly due to the fact that in Manchester coding, transition edges are used to carry information and much of the payload power is pushed into high frequency region, thus reducing the spectral overlap between payload and label[9]. This can also be verified in Fig. 3 as the MC spectrum shows a much higher frequency component.

For a fixed ER value, BER versus the received optical power for both NRZ and Manchester cases is shown in Fig. 6. We use the optimum ER for both systems, being 5 and 9 dB, respectively. It can be easily seen that the optical Manchester coding shows better performance for both payload and label.

In conclusion, the application of optical Manchester coding in a FSK/IM orthogonal modulation system is studied by simulation. With a DD-MZM, optical MC signal can be obtained and used as high-speed payload to combine with FSK modulated label, forming an optical labeling packet for OLS/OPS network. Simulation results prove the feasibility of this scheme, and a comparison between MC and traditional NRZ payloads is made. It is verified that with MC payload, the optimal ER for FSK/IM system can greatly increase, without much power penalty or BER increment. Also, a better BER performance for both payload and label is achieved with the same received optical power.

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