Encoding ASK Labeled CSRZ-DPSK Payload by Using Only One Dual-Drive Mach–Zehnder Modulator With Enhanced Label Performance

Wei-Ren Peng, Yu-Chang Lu, Jason (Jyehong) Chen, and Sien Chi

***Abstract*—This theoretical study presents a novel modulation scheme which simultaneously encodes the amplitude shift keying label on the carrier-suppressed return-to-zero differential phase shift keying payload using only one dual-drive Mach–Zehnder modulator. Compared with the previous scheme, in which three optical modulators are required, we offer a simple, compact, and cost-effective method. We theoretically evaluate and simulate the performance differences between the two schemes. It is found that the sensitivity of the label is 2 dB better than the previous scheme and the payload, with optimized extinction ratio in the electroabsorption eraser, has almost the same performance after 120-km standard single-mode fiber transmission.**

***Index Terms*—Amplitude shift keying (ASK), carrier-suppressed return-to-zero differential phase shift keying (CSRZ-DPSK), optical packet switching.**

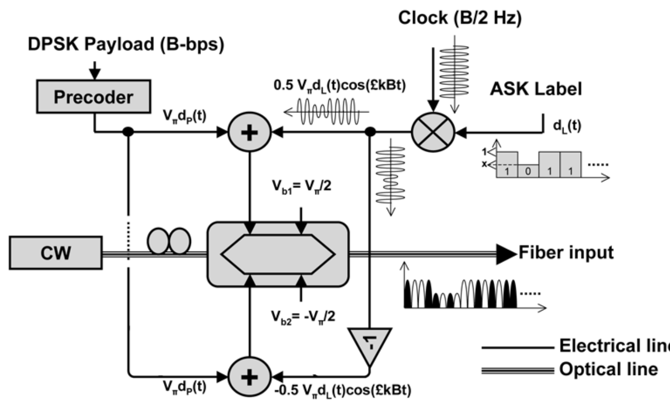

Fig. 1. Proposed scheme for ASK/CSRZ-DPSK modulation.

I. Introduction

OPTICAL label switching had been proposed to enable more effective and flexible utilization of the capacity of wavelength-division-multiplexing optical networks [1]. Optical-label packet transmission based on amplitude shift keying/return-to-zero differential phase shift keying (ASK/RZ-DPSK) orthogonal modulation format was recently proposed [2], [3], in which the payload is modulated by RZ-DPSK format, while the label is transmitted by ASK format. It was found that when DPSK is used for high-speed payload transmission (40 Gb/s and beyond), the temperature stability and polarization insensitivity of the delay interferometer are significantly improved after the laser linewidth requirements are reduced [2]. A variation over the standard RZ-DPSK is carrier-suppressed return-to-zero DPSK (CSRZ-DPSK) format. It has been shown that CSRZ-DPSK is more resilient to fiber nonlinearity and, with optical signal filtering, is the optimized format for achieving ultrahigh spectral efficiency (0.8 b/s/Hz) at 40 Gb/s [4], [5]. However, to implement such an ASK/CSRZ-DPSK orthogonal modulation format, three cascaded optical modulators are required for phase encoding, pulse carving, and label impressing [2], [3], an arrangement that is extremely costly and difficult to manage due to the size and the electronic components required in each modulator. In addition, the heritage loss is usually so high that two erbium-doped fiber amplifiers (EDFAs) will be needed in the transmitting end.

In this letter, we propose a simple and elegant method to generate ASK/CSRZ-DPSK signal which only needs one dual-drive Mach–Zehnder modulator (DD-MZM). Similar schemes producing CSRZ-DPSK signal with one DD-MZM can be found in [6] and [7]. We theoretically study and compare the performance differences between these two schemes with 40-Gb/s CSRZ-DPSK payload and 1.25-Gb/s ASK label over 120-km standard single-mode-fiber (SSMF) transmission. It is found that, under our new scheme, the receiver sensitivities of the label signal is 2 dB better, while the payload is only 0.2 dB worse than the previous scheme after 120-km SSMF transmission.

II. Principle of Operation

Fig. 1 shows the principle of the proposed scheme. The label signal is first modulated onto a half payload data rate clock. Then the precoded payload and label are synchronously combined and sent into the DD-MZM, with one arm of label signal being inverted. The output electric field $E_{\rm out}$ can be written as [8]

$$E_{\rm out} = \frac{E_{\rm in}}{\alpha^{1/2}} e^{j\left(\frac{V_1+V_2}{2v_\pi}\pi\right)} \cos\left(\frac{V_1-V_2}{2v_\pi}\pi\right) = \frac{E_{\rm in}}{\alpha^{1/2}} e^{j\pi d_p(t)} \cos\left(\frac{1}{2}\pi d_L(t)\cos(2\pi f_c t) + \frac{\pi}{2}\right) \quad (1)$$

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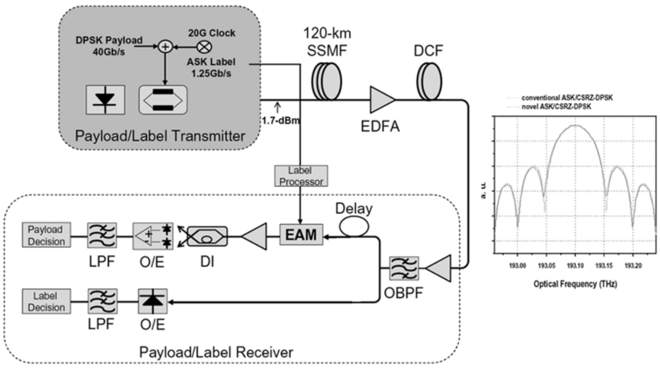

Fig. 2. System test link for the novel modulation scheme.

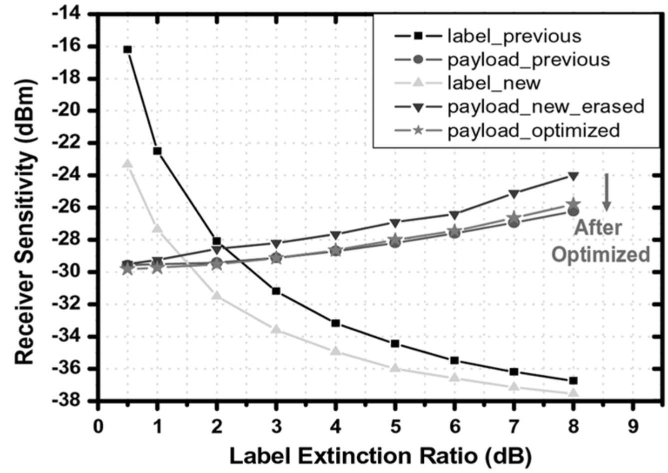

Fig. 3. Back-to-back receiver sensitivities of label and payload versus label ER.

where α and V_π are the power loss and the switching voltage of the modulator. $V_1 = V_\pi d_P(t) + 0.5\, V_\pi d_L(\mathrm{t}) \cos(2\pi \mathrm{f_c t}) + \mathrm{V_{b1}}$ and $V_2 = V_\pi d_P(t) - 0.5\, V_\pi d_L(t) \cos(2\pi f_c t) + V_{b2}$ are voltages employed on the two electrode arms. $d_L(t) = \{x, 1\}$ is the label signal which modulates the clock with a frequency of $f_c = \mathbf{B}/2$, where "x" is the electrical level representing label bit "0" range between (0, 1) depending on the required optimized extinction ratio (ER) of the label. Bias voltages on the two arms V_{b1} and V_{b2} are $+V_\pi/2$ and $-V_\pi/2$, respectively, which bias the MZM at the null point of transmission curve. The first term of E_{out} contains the phase information encoded by the payload and the second term carves the payload into pulses with the label modulated clock. Thus, the MZM output will contain CSRZ-DPSK payload with impressed ASK label. Notably, in practice, the "+" in Fig. 1 can be realized using a linear radio-frequency combiner/coupler, and the "-1" can be implemented using a π-phase shifter. Since the pulse carving clock is amplitude modulated, the output pulses of the payload will have label-dependent duty cycle. Thus, the spectrum of the payload will be label-dependent, which might introduce label interference to the payload after narrow-band filtering. However, a simple adjustment of the eraser ER can easily alleviate the label interference effect with minimum impact on the system performance.

III. System Setup and Theoretical Results

To demonstrate the feasibility of the proposed scheme, a transmission link is established as shown in Fig. 2, which contains three main parts: payload/label transmitter, transmission fiber, and payload/label receiver. A 40-Gb/s CSRZ-DPSK payload with 1.25-Gb/s label is generated and transmitted with input power of 1.7 dBm over 120-km SSMF with fiber loss of 0.2 dB/km, dispersion parameter of $D = 16$ ps/(nm)(km), and nonlinear coefficient $r = 1.314$ (1/W $\cdot$ km). The signal is then amplified using the inline EDFA with 20-dB gain and 5-dB noise figure and the SSMF dispersion is fully compensated by the following dispersion compensating fiber in a postcompensation scheme. At the receiving end, the signal is optically amplified by an EDFA with 30-dB gain and 5-dB noise figure and then passes through a second-order Gaussian filter with a 3-dB bandwidth of 2.4 nm. It is then split into two branches for payload and label extraction. In the upper branch, the ASK label is erased by an electroabsorption modulator. As suggested in [2], the transmitted label is inverted and directly fed into the remote label erasure to focus on new scheme performance. A delay-interferometer is used to demodulate the CSRZ-DPSK payload and detected by a balanced-photodiode. The fourth-order Bessel electrical filter with a 3-dB bandwidth of 30 GHz is used to eliminate the residual noise. In the lower branch, the signal is directly fed into a photodiode and goes through a low-pass fourth-order Bessel filter with a 3-dB bandwidth of 1 GHz to extract the label information. For comparison, we also simulated previous proposed scheme [2], [3] with the same system parameters as our new scheme.

The performance evaluation was conducted using a commercial simulation tool, VPItransmissionMaker 5.0. Both the input payload and label data are rectangular pulse, and the sequence used is the pseudorandom binary sequence patterns with length $2^{11} - 1$. The simulation time window is set to 1.64 μs which allow sufficient bit number of label and payload ($\geqq 2048$) for more accurate estimation of bit-error rate (BER). BER is calculated using the Gaussian detection statistics for both payload and label [4].

The inset in Fig. 2 shows the optical spectra of ASK/CSRZ-DPSK signals using the conventional and proposed schemes. No difference is apparent between these two schemes except that the new scheme has a slightly broader main lobe. This may result from the reduced duty cycle of the pulses impressed by label bit "0."

Fig. 3 shows the back-to-back receiver sensitivities of the payload and label as a function of the label ER at $\mathrm{BER} = 10^{-12}$. As expected, the tradeoff between the ER requirements for the label and payload are observed. In the previous scheme [2], the duty cycle of CSRZ-DPSK is fixed, and thus, the eraser can simply use the inverted label signal to remove the label. In the proposed scheme, the payload spectrum comprises two spectra from pulses with different duty cycles, corresponding to the impressed label bits "one" and "zero." The two spectra produce different filtering effect following a narrow-band electrical filter and, thus, lead to label interference with payload detection. Fig. 4 shows that, without optimization, electrical filtering produces a multilevel eye diagram. However, with a slightly larger ER (3.6 dB, if the original ER of the label is 3 dB) in the

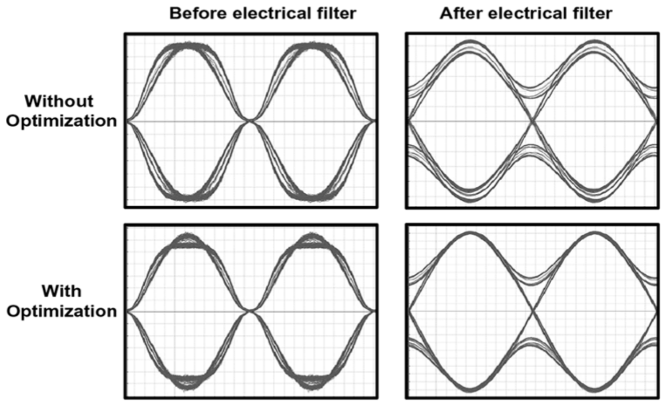

Fig. 4. Eye patterns of the payload before and after the low-pass electrical filter, with and without the optimization scheme.

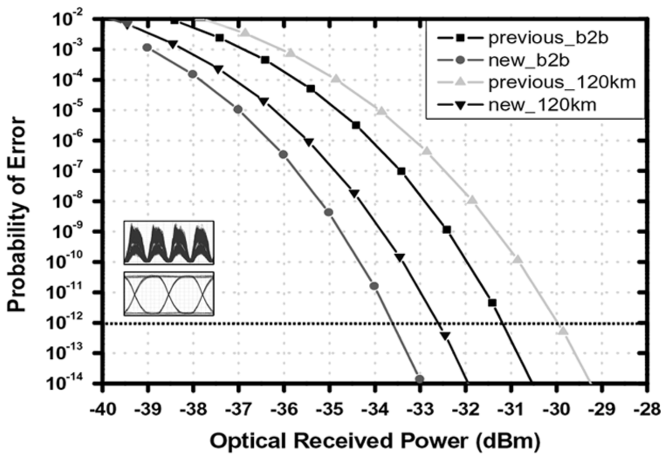

Fig. 5. BER performances of the label in back-to-back and 120-km SSMF transmission.

eraser, a single level eye diagram at the decision point can be obtained after optimization. Conventionally, because the label carries routing information and is necessitated to have better sensitivity than the payload [9], we choose the label ER equal to 3 dB in both schemes for fair comparison. BERs of the labels are shown in Fig. 5. The inset shows the transmitted label patterns before and after filtering with 1-GHz electrical low-pass filter. Comparing these two schemes, the new scheme has 2 dB better label performance owing to the smaller duty cycle of the payload, indicating a larger distance between the mark and space levels [10]. Additionally, the narrower pulses (space) are filtered out more power than the broader pulses (mark), thus enlarging the ER of the label after narrow-band electrical filtering. Fig. 6 shows the BER results of the payload. In both back-to-back and after 120-km SSMF transmission, the sensitivities of the optimized payload at BER $= 10^{-12}$ are only 0.2 dB worse than the previous scheme. These results clearly indicate that the new scheme has better label sensitivity, which is crucial in the packet switching network, almost the same payload performance and much lower cost since only single modulator is needed.

IV. Conclusion

We propose a novel scheme which generates ASK/CSRZ-DPSK signals using only one DD-MZM. By synchronously combining the payload data with the pulse carving clock modulated by label, the new method is much simpler and more cost-effective because only a single modulator and no EDFA is required. Performance of the novel scheme is studied and investigated theoretically. We setup a transmission link with 40-Gb/s CSRZ-DPSK payload impressed by 1.25-Gb/s ASK label over 120-km SSMF. It is found that the label is 2 dB better than the previous scheme and the payload has only 0.2 dB worse sensitivity at BER $= 10^{-12}$.

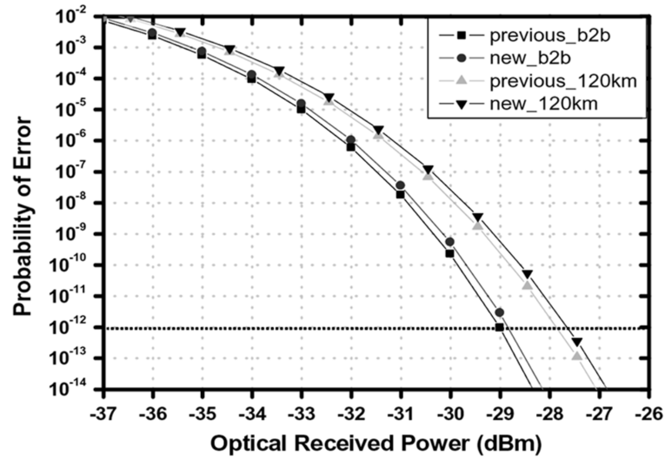

Fig. 6. BER performances of the payload in back-to-back and 120-km SSMF transmission.

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