Time Skew-based Filter-free VSB Nyquist PAM-4/6 Generation and 80km SSMF Transmission with Direct Detection

Yixiao Zhu, Longsheng Li, Xin Miao, Weisheng Hu

State Key Laboratory of Advanced Optical Communication System and Networks, Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai, 200240, China, wshu@sjtu.edu.cn

Abstract *We propose a novel filter-free VSB generation scheme based on time skew with single DAC, and experimentally transmit 38Gbaud Nyquist PAM-4/6 signals over 80km dispersion uncompensated SSMF link with 40GSa/s ADC, achieving 7% and 20% HD-FEC thresholds, respectively.*

Introduction

The capacity demand of intra- and inter-data center interconnects (DCI) are growing rapidly, in order to accommodate the Internet traffic driven by the cloud, video and data services. Intensity modulation with direct detection (IM-DD) has dominated short-reach links because of its simplicity and low cost [1]. However, fiber chromatic dispersion (CD) induced power fading effect would bring notches inside the signal spectrum of IM-DD links, and the transmission distance is thus severely limited [2].

So far, lots of efforts have been made to deal with the fading problem. In the optical domain, O-band transmission around the zero-dispersion wavelength [3], dispersion compensation fiber (DCF) module [4], and vestigial sideband (VSB) reception based on optical filter [5] are three main approaches. However, these methods would result in larger transmission loss and significantly increase the system cost. On the other hand, digital-domain techniques, such as block-wise phase switching (BPS) [6], CD pre-compensation [7] and single sideband signalling (SSB) with Kramers-Kronig detection [8,9], have attracted many attentions in recent years. One shortcoming is that 2 digital-to-analog convertors (DACs) are used at the transmitter together with IQ modulator or dual-drive Mach-Zehnder modulator (DDMZM), in order to generate complex-valued waveforms. Therefore, the hardware complexity and cost are much higher than conventional IM-DD systems.

In this work, a novel filter-free VSB transmitter is proposed and experimentally demonstrated. With optimized time skew between the differential arms of the Mach-Zehnder modulator (MZM), the power fading can be mostly avoided. With 40GSa/s analog-to-digital convertor (ADC), we successfully transmit 38Gbaud Nyquist 4/6-ary pulse amplitude modulation (PAM-4/6) over 80km standard single-mode fiber (SSMF) without dispersion compensation. The bit-error rates (BERs) can reach the 7% and 20% hard-decision forward error correction (HD-FEC) thresholds of 4.5×10^{-3} and 1.5×10^{-2}, respectively.

Principle

As shown in Fig.1(a), in conventional IM-DD system, double sideband (DSB) signal can be generated with a single DAC by operating at differential-drive mode or single-drive push-pull mode of MZM. Meanwhile, SSB transmitter is implemented based on the suposition of intensity waveform $s(t)$ and its Hilbert transform $H\{s(t)\}$ from two DACs as in Fig.1(b). Differently, the principle of the proposed filter-free VSB transmiter is shown in Fig.1(c). By introducing time skew τ between the differential driving signals on the upper and lower arms of the MZM, the output optical field can be calculated as follows:

$$\begin{aligned} E_o(t) &= \exp\left[js(t)+j\varphi\right]+\exp\left[-js(t-\tau)-j\varphi\right] \\ &\approx e^{j\varphi}\left[1+js(t)\right]+e^{-j\varphi}\left[1-js(t-\tau)\right] \\ &= C+j\left[e^{j\varphi}s(t)-e^{-j\varphi}s(t-\tau)\right]. \end{aligned} \tag{1}$$

Here φ is the bias induced phase shift, and the approximation $e^x \approx 1+x$ is used. The 1st-term C is the constant optical carrier. To understand the mechanism more clearly, we apply Fourier transform on Eq.(1) to see the signal spectrum.

$$\begin{aligned} FFT\{E_o(t)\} &= C+j\left[e^{j\varphi}S(f)-e^{-j\varphi}S(f)e^{-j2\pi f\tau}\right] \\ &= C+j\left(e^{j\varphi}-e^{-j\varphi}e^{-j2\pi f\tau}\right)S(f) \\ &= C-2e^{-j\pi f\tau}\sin(\varphi+\pi f\tau)S(f) \end{aligned} \tag{2}$$

Here $S(f)$ is the Fourier transform of $s(t)$, and the property $FFT\{s(t)\}=S(f)e^{-j2\pi f\tau}$ is employed. Assuming the MZM is biased at the quadrature point, then $\varphi=3\pi/4$ is substituted into Eq.(2).

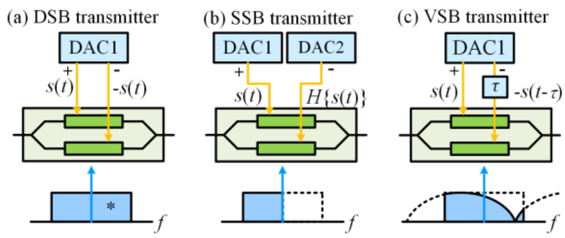

Fig.1: Structure and optical spectra of (a) DSB, (b) SSB, and (c) proposed VSB transmiter, respectively.

Therefore, it can be found that the envelop of the signal spectrum is shaped by $\sin(\pi/4+\pi f\tau)$, which is asymmetrical with reference to the zero frequency. Moreover, the position of notch and the edge roll-off can be changed by adjusting the skew value τ. In the following proof-of-concept experiment, τ is introduced digitally. For practical implementation, electrical delay line might be used for differential-drive mode, while optical delay line can be integrated with MZM for single-drive push-pull mode.

Experimental Setup and DSP stack

The experimental setup of 38Gbaud VSB Nyquist PAM-4/6 80km SSMF transmission is shown in Fig.2. An external cavity laser (ECL) is employed to generate the optical carrier centered at 1550.2nm, which is fed into the DDMZM. After electrical amplifiers (EAs), the differential outputs of the arbitrary waveform generator (AWG, Keysight M8195) operating at 64GSa/s modulates the optical carrier. Skew is adjusted for VSB shaping through the software IQ tools inside the AWG. Before transmission, an erbium-doped optical amplifier (EDFA) is utilized to control the launching power. The fiber link is 80km SSMF without inline dispersion compensation.

At the receiver, the optical signal is firstly amplified by EDFA. Then O-E conversion is conducted directly by using 40GHz photodiode (PD) without optical filtering. The electrical waveform is sampled and quantized with digital storage oscilloscope (DSO, LeCroy SDA 845Zi-A) operating at 40GSa/s. Offline digital signal processing (DSP) is performed later in MATLAB. It should be noted that higher baud rate is still possible with the proposed scheme, if the sampling rate of DSO is increased.

The transmitter- and receiver-side DSP are shown in Fig.3(a) and 3(b). Firstly, PAM-4/6 symbols are mapped from binary sequence. The added preamble consists of a 64-symbol sequence for synchronization, and a 2048-symbol sequence for channel estimation. After 2-times up-sampling, root raised cosine (RRC) filter with 0.05 roll-off is applied to realize a

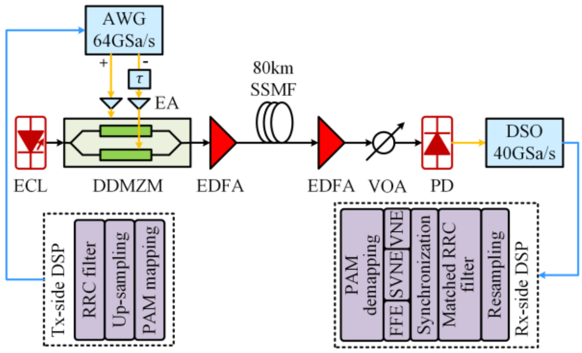

Fig.2: Experimental setup. ECL: external cavity laser; AWG: arbitrary waveform generator; EA: electrical amplifier; DDMZM: dual-drive Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier; SSMF: standard single-mode fiber; VOA:variable optical attenuator; PD: photodiode; DSO: digital oscilloscope; Tx: transmitter; Rx: receiver; RRC: root-raised cosine; FFE: feed forward equalizer; (S)VNE: (sparse) Volterra nonlinear equalizer.

rectangular-like signal spectrum. The waveform is resampled to 38Gbaud before sending to the AWG. Here no pre-equalization is conducted.

At the receiver, the captured waveform is resampled to 4 samples per symbol (SPSs). Then the synchronized sequence is down sampled to 2 SPSs before equalization. The taps of time-domain T/2-spaced finite impulse response (FIR) filter is updated by recursive least square (RLS) algorithm based on training sequence. Here linear feed forward equalizer (FFE), sparse Volterra nonlinear equalizer (SVNE) with diagonal terms only, and full Volterra nonlinear equalizer (VNE) are employed for comparison. Finally, BER is obtained after symbol decision and de-mapping with ~4×10^5 bits.

Experimental results and discussion

Fig.3(a) shows the optical spectra with different skew values at the transmitter with 0.02nm resolution. When the skew value is increased from 0ps to 13ps, the spectra is gradually transformed from DSB to VSB. Further increment moves the notch closer to the zero frequency. The optical extinction ratio is ~20dB, which is enough for VSB filtering. Fig.3(b) compares the optical spectra at back-to-back (BTB) case and after 80km SSMF transmission, respectively. There is 4.9dB optical signal-to-

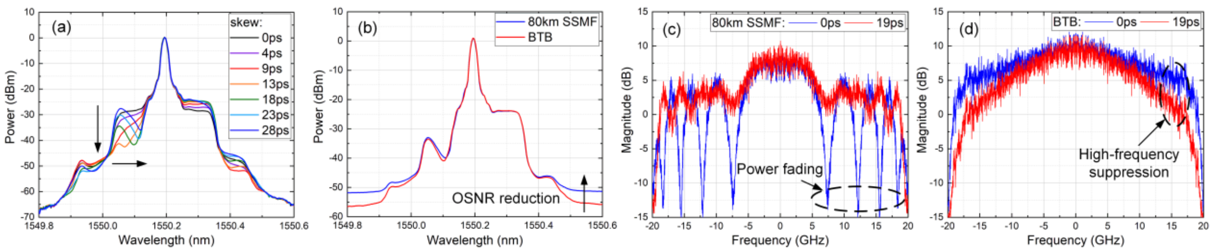

Fig.3: (a) Optical spectra with different time skew at the transmitter. (b) Transmitted and received optical spectra with 0.02nm resolution. (c) Electrical spectra of detected waveform after 80km SSMF transmission with 0/19ps skew. (d) Electrical spectra of detected waveform at BTB with 0/19ps skew.

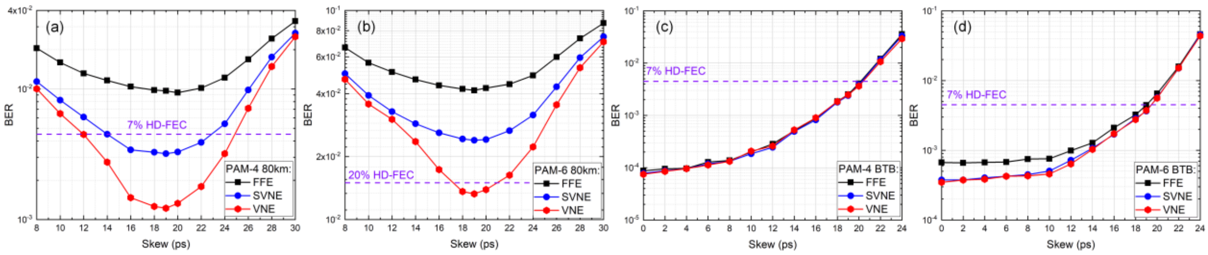

Fig.4: Measured BER versus skew for (a) PAM-4 and (b) PAM-6 signals after 80km SSMF transsmission, respectively. Measured BER versus skew for (c) PAM-4 and (d) PAM-6 signals at BTB, respectively.

noise ratio (OSNR) reduction after transmission, which can be also confirmed by the rising level of out-of-band ASE noise.

Fig.3(c) depicts the electrical spectra with 0ps and 19ps after 80km SSMF transmission. For DSB transmission (0ps), multiple nulls can be observed inside the signal bandwidth due to the power fading. With 19ps skew, the notches can be mostly avoided, leading to less severe inter-symbol interference (ISI). At BTB case, skew would bring additional penalty results from the slightly suppressed high-frequency as in Fig.3(d).

Fig.4(a) and 4(b) plot the measured BER as a function of skew for PAM-4/6 signal after 80km SSMF transmission, respectively. The optimal skew value is 19ps. Smaller skew would result in low-frequency region fading, while larger skew makes the high-frequency components fade again. With the help of SVNE, the BERs of PAM-4/6 can be reduced from 9.67×10^{-3} and 4.15×10^{-2} to 3.20×10^{-3} and 2.39×10^{-2} compared with FFE only at 19ps skew. The BERs are further decreased to 1.22×10^{-3} and 1.33×10^{-2} if full VNE is used. The tap numbers of FFE and SVNE/VNE are 141 and (141,29,5), respectively. On the other hand, the BTB case is also measured as in Fig.4(c) and 4(d). The skew is optmized as 0ps for PAM-4/6 signals, which concidences with conventional knowledge. Also it should be noted that since there is much less nonlinear impairment at BTB, (S)VNE brings negligible improvement compared with FFE.

Fig.5(a) and 5(b) show the measured BER versus received optical power (ROP) for PAM-4/6 signals after 80km SSMF transmission, respectively. For DSB signal with 0ps skew, the BER is larger than 0.1 even with VNE. Thanks to the VSB shaping with 19ps, PAM-4/6 can reach the 7% HD- and 20% SD-FEC thresholds of 3.20×10^{-3} and 2.39×10^{-2} by using SVNE, considering both performance and computational complexity. Furthermore, VNE achieves the lowest BER, with the sensitivity of -5.1dBm and -1.3dBm for PAM-4/6 signals, respectively. At the BTB case as in Fig.5(c) and 5(d), differential drive mode with 0ps is better than 19ps. The penalties are 2.2dB and 2.0dB at the 7% HD-FEC for PAM-4 and at the 20% HD-FEC for PAM-6 signals, respectively. Such penalty can be removed if the skew value is tuneable in the proposed VSB transmitter.

Conclusions

In summary, a novel filter-free VSB transmitter is put forward and experimentally demonstrated. With optimized time skew between the differential arms of the MZM, the power fading can be successfully avoided. With 40GSa/s ADC, 38Gbaud Nyquist PAM-4/6 is transmitted over 80km SSMF without dispersion compensation. The BERs can achieve the 7% and 20% HD-FEC, respectively. We believe the proposal would provide a cost-effective solution for high-speed intra- and inter-DCI applications.

Acknowledgements

This work is supported by National Key Research and Development Program of China (2018YFB1800904); National Natural Science

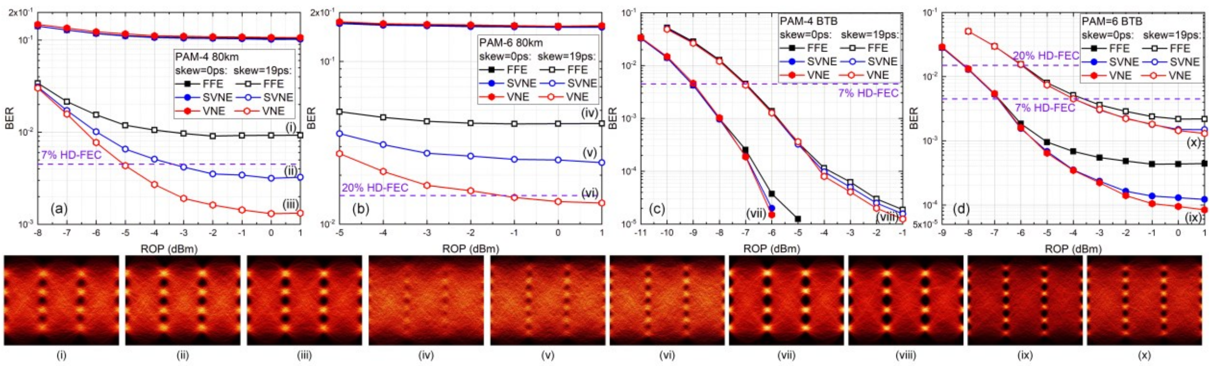

Fig.5: Measured BER versus received optical power (ROP) for (a) PAM-4 and (b) PAM-6 signals after 80km SSMF transmission, respectively. Measured BER versus ROP for (c) PAM-4 and (d) PAM-6 signals at BTB scenario, respectively. (i)~(x) Typical eyediagrams after equalization.

Foundation of China (NSFC) (61431009).

References

[1] K. Zhong, X. Zhou, J. Huo, C. Yu, C. Lu, and A. P. T. Lau, "Digital Signal Processing for Short-Reach Optical Communications: A Review of Current Technologies and Future Trends," Journal of Lightwave Technology, 36(2), 377-399 (2018).

[2] Di Che, Q. Hu, and W. Shieh, "Linearization of Direct Detection Optical Channels Using Self-Coherent Subsystems," Journal of Lightwave Technology, 34(2), 516-524 (2016).

[3] J. Zhang, J. Yu, H. Chien, J. S. Wey, M. Kong, X. Xin, and Y. Zhang, "Demonstration of 100-Gb/s/λ PAM-4 TDM-PON Supporting 29-dB Power Budget with 50-km Reach Using 10G-class O-band DML Transmitters," in OFC2019, paper Th4C.3.

[4] N. Eiselt, J. Wei, H. Griesser, A. Dochhan, M. Eiselt, J.-P. Elbers, J. J. V. Olmos, and I. T. Monroy, "First Real-Time 400G PAM-4 Demonstration for Inter-Data Center Transmission over 100 km of SSMF at 1550 nm," in OFC2016, paper W1K.5.

[5] J. Lee, N. Kaneda, and Y. K. Chen, "112-Gbit/s Intensity-Modulated Direct-Detect Vestigial-Sideband PAM4 Transmission over an 80-km SSMF Link," in OFC2016, paper M.2.D.3.

[6] X. Chen, A. Li, D. Che, Q. Hu, Y. Wang, J. He, and W. Shieh, "Block-wise phase switching for double-sideband direct detected optical OFDM signals," Optics Express, 21(11), 13436-13441 (2013).

[7] Q. Zhang, N. Stojanovic, C. Xie, C. Prodaniuc, and P. Laskowski, "Transmission of single lane 128 Gbit/s PAM-4 signals over an 80 km SSMF link, enabled by DDMZM aided dispersion pre-compensation," Optics Express, 24(21), 24580-24591 (2016).

[8] L. Zhang, T. Zuo, Y. Mao, Q. Zhang, E. Zhou, G. N. Liu, and X. Xu, "Beyond 100-Gb/s Transmission Over 80-km SMF Using Direct-Detection SSB-DMT at C-Band," Journal of Lightwave Technology, 34(2), 723-729 (2016).

[9] A. Mecozzi, C. Antonelli, and M. Shtaif, "Kramers-Kronig coherent receiver," Optica, 3(11), 1220-1227 (2016).