This is the Pre-Published Version.
The following publication Y. Xu et al., "260-Gb/s PAM-6 Transmission Using Joint Optical Pre-equalization and a Low-complexity Volterra Equalizer for Short-Reach Optical Interconnects," 2018 Asia Communications and Photonics Conference (ACP), Hangzhou, China, 2018 is available at https://doi.org/10.1109/ACP.2018.8595838.

260-Gb/s PAM-6 Transmission Using Joint Optical Pre-equalization and a Low-complexity Volterra Equalizer for Short-Reach Optical Interconnects

Yongsheng Xu[1], Junwei Zhang[2], Baoxian Yu[2,4], Sen Zhang[3], Tianjian Zuo[3], Lei Liu[3], Jie Liu[2], Changjian Guo[1,4*], Alan Pak Tao Lau[5], Chao Lu[4]

[1]*South China Academy of Advanced Optoelectronics, South China Normal University, Guangzhou 510006, China*
[2]*State Key Laboratory of Optoelectronic Materials and Technologies, School of Electronics and Information Technology, Sun Yat-Sen University, Guangzhou 510006, China*
[3]*Network Technology Laboratory, Huawei Technologies Co., Ltd., Shenzhen 518129, China*
[4]*Photonics Research Center, Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China*
[5]*Photonics Research Center, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China*
**changjian.guo@coer-scnu.org*

***Abstract*—We experimentally demonstrate a 260-Gbit/s PAM-6 transmission over 500-m SSMF using optical pre-equalization and a simplified Volterra nonlinear feed-forward and decision-feedback equalizer (NL-FFE-DFE), achieving the BER below the 7% forward error correction threshold.**

Keywords—IMDD, PAM-6, Optical interconnects.

I. INTRODUCTION

With the continuously growing popularity of Internet applications, such as 4K/8K display, cloud computing, Augmented Reality/Virtual Reality (AR/VR), etc., data-center traffic has increased dramatically, which drives the demand for high-capacity short-reach interconnections []. To further increase the data rate, the next-generation interfaces aim at 800 Gigabit Ethernet or 1.6 Terabit Ethernet (1.6 TE), in which the per channel data rate reaches up to 200-Gbit/s or even higher []. Recently, short-reach optical transceivers with over 200-Gbit/s data rate have been reported []. In such works, various schemes for intensity modulation and direct detection (IM-DD) have been proposed to improve the system capacity whilst maintaining the simplicity and reliability. Among them, advanced modulation formats like pulse amplitude modulation (PAM) and orthogonal discrete multi-tone (DMT) have attracted a lot of interest due to their improved spectral efficiency []. Among them, PAM (PAM-4 in particular) can offer better balanced performance and computational complexity, and has been used in 100G/400G Ethernet standards. However, for per channel data rate of larger than 200 Gb/s, the bandwidth requirements for PAM-4 signaling is prohibitive. Meanwhile, higher order PAM signaling, such as PAM-8, requires much higher SNR compared with PAM-4. Compared with PAM-4 and PAM-8, PAM-6 is regarded as a more attractive format for over 200-Gb/s short-reach applications in terms of system performance and implementation complexity. Besides advance modulation formats, digital signal processing (DSP) methods such as feed-forward equalization (FFE), decision feedback equalization (DFE), maximum likelihood sequence estimation (MSLE), and Volterra series based nonlinear equalization (VNLE) have been utilized to improve the transmission performance.

In this work, we elaborate on the topic of 3^{th} order simplified Volterra nonlinear feed-forward and decision-feedback equalizer (NL-FFE-DFE) and experimentally demonstrate a 260-Gbit/s PAM-6 short-reach optical system using commercial available components over 500-m SSMF transmission. Also, an optical pre-equalizer (OEQ) is used at the transmitter in order to further enhance the SNR. The bit error ratio (BER) below the 7% hard-decision forward error correction (FEC) limit is achieved after 500-m SSMF transmission.

II. PRINCIPLE

For short-reach IM/DD transmission systems operating at C-band, nonlinear distortions caused by electrical amplifiers, electro-optic modulators and photodiodes may deteriorate the system performance and limit the capacity. To effectively compensate these nonlinear distortions and limit the complexity, a simplified Volterra based NL-FFE-DFE can be utilized in optical fiber systems. Fig.1 shows the structure of the Volterra NL-FFE-DFE, where $x(n)$ is the sample of the received signal, N_b (b = 1, 2, 3) and L_b (b=1, 2, 3) are the memory length of the b^{th}-order term for FFE and DFE, respectively.

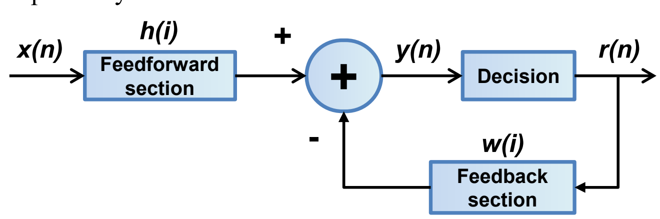

Fig.1 The structure of the Volterra NL-FFE-DFE

The equalizer output is given by

$$y(n) = A(n) + B(n) + C(n) - D(n) - E(n) - F(n) \quad (1)$$

where

$$A(n)=\sum_{i=0}^{N_1-1}h_1(i)x(n-i)$$

$$B(n)=\sum_{i,j=0}^{N_2-1}h_2(i,j)x(n-i)x(n-j)$$

$$C(n)=\sum_{i=0}^{N_3-1}h_3(i)x^3(n-i)$$

$$D(n)=\sum_{i=1}^{L_1}w_1(i)x(n-i)$$

$$E(n)=\sum_{i,j=1}^{L_2}w_2(i,j)r(n-i)r(n-j)$$

$$F(n)=\sum_{i=1}^{L_3}w_3(i)r^3(n-i)$$

h_b (b = 1, 2, 3) and w_b (b=1, 2, 3) are the coefficients of the b^{th}-order term for FFE and DFE, respectively. $r(n)$ represents the symbols after hard decision. The optimum equalizer coefficients can be found using the low computational complexity least mean squares (LMS) algorithms or the recursive least-square (RLS) algorithms with fast convergence.

III. Experimental Setup and Results

A block scheme of the experimental setup is illustrated in Figure 2. At the transmitter, a pseudo random bit sequence (PRBS) is mapped into a QAM-32 constellation. The PAM-6 symbols are obtained by splitting the real and imaginary part of the QAM-32 signals. The output PAM-6 signals are then loaded into an arbitrary waveform generator (AWG, with 35-GHz 3-dB bandwidth). The electrical PAM-6 signals from the AWG, ranging from 100 Gbaud to 106 Gbaud by varying the sampling rate from 100 GSa/s to 106 Gsa/s, are sent to a linear amplifier (SHF s807) to boost the electrical signal before it is sent to a Mach-Zehnder modulator (MZM, 32GHz bandwidth) for double side-band (DSB) electrical-optical conversion. The optical carrier used in this experiment has a center wavelength of 1550.13 nm and is generated from a distributed feedback (DFB) laser. Before fiber transmission, the modulated signals are sent to a programmable optical filter (Finisar Waveshaper) which is used as an optical equalizer (OEQ) to further enhance the SNR []. The optical spectra before and after the OEQ are shown in Fig.3. After 500-m SSMF transmission, the optical signal is send to a pre-amplified optical receiver which consists of a variable optical attenuator (VOA), an Erbium doped fiber amplifier (EDFA) followed by an optical band pass filter (BPF) and 40-GHz photo detector (PD). Finally, the photo detected signals are digitized and sampled by a 59-GHz real time oscilloscope (OSC) operated at 160GSa/s. This is followed by off-line DSP procedures including resampling, pre-filtering, timing phase recovery, Volterra DFE, demodulation and bit error counting. In order to avoid aliasing, a root raised cosine (RRC) pulse shaping filter with a roll-off factor of 0.2 is used for pulse shaping.

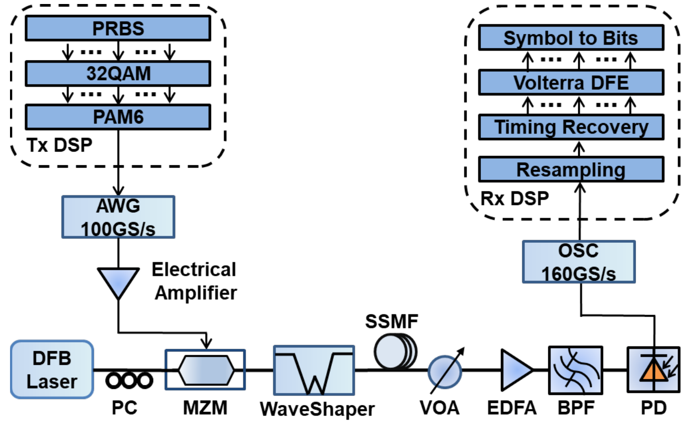

Fig.2. Experiment setup and DSP block diagram

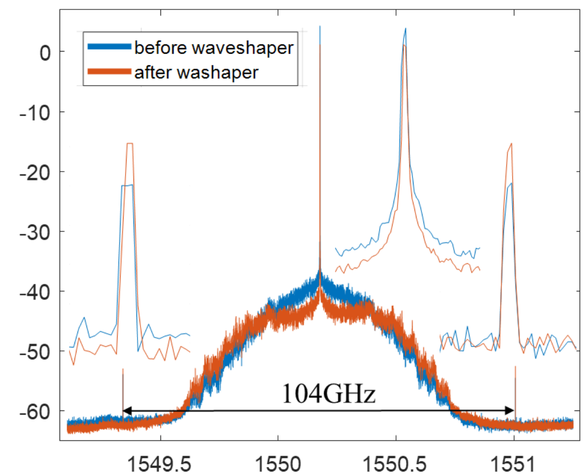

Fig.3 The measured optical spectra

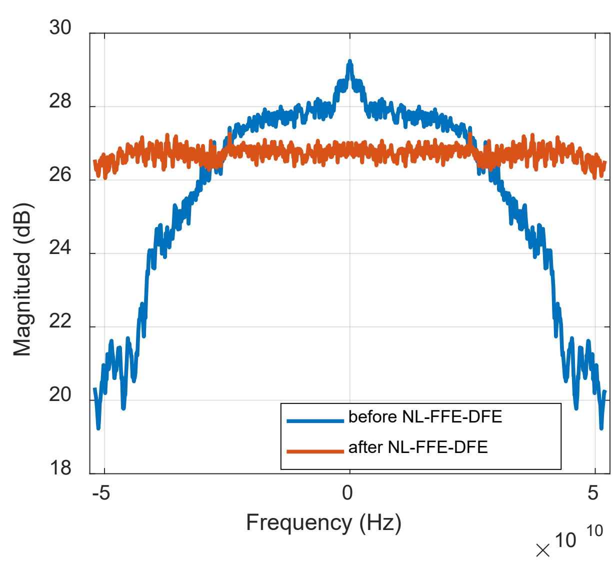

Figure 3. show the measured optical spectra

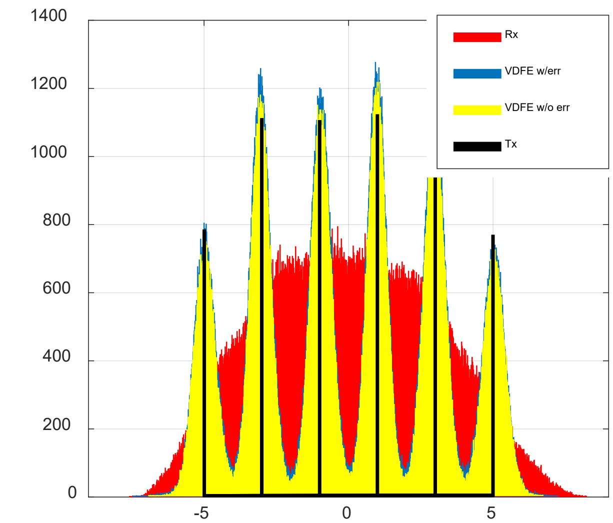

Fig. Historgam of 260Gbit/s PAM-6

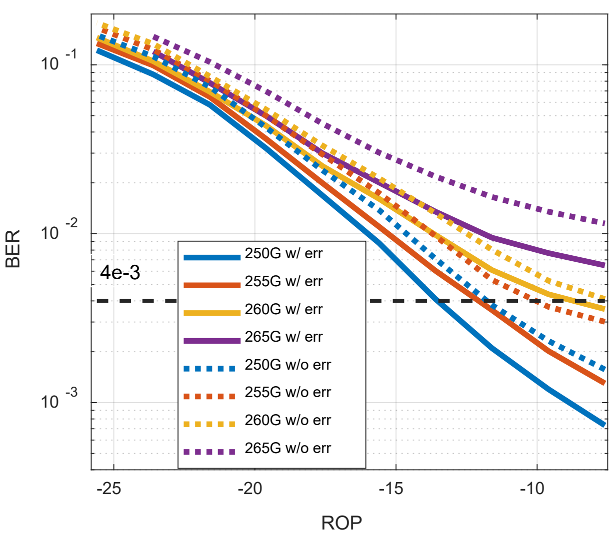

Fig.3 Measure BER versus ROP of two scheme at difference data rate after 500-m SSMF transmission.

Fig.3 shows the measured BER performance versus ROP for 250Gb/s to 265Gb/s PAM-6 after 500-m SSMF transmission. NL-FFE-DFE

Solid line and dot line represents actual results using Voterra NL-FFE-DFE (with error propagation) and results when all symbols are regarded as training symbols (without error propagation), respectively. The BER results of 100-Gbaud, 102-Gbaud, 104-Gbaud, and 106-Gbaud PAM-6 results are considered, corresponding to a data rate of 250-Gb/s, 255-Gb/s, 260-Gb/s and 265-Gb/s, respectively. One can see from Fig.* that the BER dropped below the 7% FEC limit for PAM-6 signals with data rates of up to 260-Gb/s. Also, one can see that compared with no error propagation cases, the actual results using Volterra NL-FFE-DFE with error propagation has a power penalty of about 2 dB for 100-Gbaud PAM-6 signals.

IV. CONCLUSIONS

In this work, we have experimentally demonstrated a 260-Gbit/s PAM-6 IM-DD transmission system using an optical pre-equalizer combined with simplified 3th order simplified Volterra NL-FFE-DFE equalization. We have shown that after 500-m SSMF transmission, the BER can be dropped below 7% FEC limit at 260Gb/s.

ACKNOWLEDGMENT

This work was supported in part by a Pearl River S&T Nova Program of Guangzhou under grant No. 201710010028, Natural Science Foundation of China under grant No. 61505266 and Natural Science Foundation of Guangdong province, China under grant No. 2016A030313289.

REFERENCES

[1] White paper: Cisco VNI Forecast and Methodology, 2016.

[2] I. S. Jacobs and C. P. Bean, "Fine particles, thin films and exchange anisotropy," in Magnetism, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.

[3] G. N. Liu, L. Zhang, T. Zuo, and Q. Zhang, "IM/DD Transmission Techniques for Emerging 5G Fronthaul, DCI, and Metro Applications, " J. Lightwave Technol. Vol. 36, pp. 560–567, January 2018.

[4] J. Shi, Y. Zhou, Y. Xu, J. Zhang, J. Yu, N. Chi, "200-Gbps DFT-S OFDM Using DD-MZM-Based Twin-SSB With a MIMO-Volterra Equalizer," in IEEE Photonics Technology Letters, vol. 29, July 2017.

[5] Y. Wang, J. Yu, ,H. C. Chien, X. Li, and N. Chi, "Transmission and direct detection of 300-Gbps DFT-S OFDM signals based on O-ISB modulation with joint image-cancellation and nonlinearity-mitigation," in European Conference on Optical Communication, 2016.

[6] J. Zhang, Y. Zheng, X. Hong, and C. Guo, "Increase in Capacity of an IM/DD OFDM-PON Using Super-Nyquist Image Induced Aliasing and Simplified Nonlinear Equalization," J. Lightwave Technol. Vol. 35, pp. 4105-4113, August 2017.

[7] J. Zhang, C. Guo, J. Liu, X. Wu, A. P. T. Lau, C. Lu, S. Yu, "Orthogonal Matching Pursuit based Sparse Nonlinear Equalization for 40-Gb/s/wavelength Long-Reach PON," in CLEO-PR. Optical Society of America, 2018, paper W2I.6.

[8] J. Zhang, C. Guo, J. Liu, X. Wu, A. P. T. Lau, C. Lu, S. Yu, "Low Complexity Frequency-Domain Nonlinear Equalization for 40-Gb/s/wavelength Long-Reach PON," in Optical Fiber Communications Conference, Optical Society of America, 2018, paper W1J.8.