128 Gbit/s high speed optical interconnection networks in data centers by a 30 GHz Mach-Zehnder modulator*

FU Jiajia**, **SHI Zhan, and ZHANG Zhengfeng**

Power Dispatching Control Center of Guangdong Power Grid Co., Ltd., Guangzhou 510030, China

(Received 1 July 2022; Revised 11 October 2022)

A decision feedback equalization (DFE) algorithm is proposed by simplifying Volterra structure. The simplification principle and process of the proposed Volterra-based equalization algorithm are presented. With the support of this algorithm, the signal damage for four-level pulse amplitude modulation signal (PAM-4) is compensated, which is caused by device bandwidth limitation and dispersion during transmission in C-band intensity modulation direct detection (IM-DD) fiber system. Experiments have been carried out to demonstrate that PAM-4 signals can transmit over 2 km in standard single-mode fiber (SSMF) based on a 30 GHz Mach-Zehnder modulator (MZM). The bit error rate (*BER*) can reach the threshold of hard decision-forward error correction (HD-FEC) (*BER*=3.8×10^{-3}) and its sensitivity is reduced by 2 dBm compared with traditional feedforward equalization (FFE). Meanwhile, the algorithm complexity is greatly reduced by 55%, which provides an effective theoretical support for the commercial application of the algorithm.

Document code: A **Article ID:** 1673-1905(2023)01-0036-5

DOI https://doi.org/10.1007/s11801-023-2119-9

To satisfy the rapidly increasing demand of bandwidth in applications, such as cloud computing, datacenter interconnects (DCI) and virtual reality (VR), the capacity of short reach applications is confronting with unprecedented challenges[1]. Due to the relatively short transmission distance (e.g., <20 km) in the transmission systems of such applications, it is imperative to realize those systems in a highly cost-effective manner. Thus, the selection of optical transport technology is largely determined by the capability of delivering high data-rate signal with low implementation and operation costs. In this case, intensity modulation and direct detection (IM/DD) systems based on pulse amplitude modulation (PAM) format have received a lot of studies because of the advantages of lower cost and higher capacity[2,3]. Meanwhile, compared to externally modulated systems employing directly modulated lasers (DMLs) or electro-absorption modulated lasers (EMLs), Mach-Zehnder modulator (MZM) exhibits superior performance for it has no chirp. However, we still need to resolve several problems when achieving an IM/DD system. The noteworthy one is the severe chromatic dispersion (CD) in C-band and limited devices bandwidth, which will cause inter-symbol-interference (ISI), thus increasing the bit error in receiver. In these years, many researchers have been focused on it to improve the system performance[3-6]. In Ref.[3], researchers have analyzed the frequency fading effect caused by dispersion with different modulated lasers and reduced the bit error rate (*BER*) by adjusting the output power or using algorithms. Meanwhile, another technical problem associated with the MZM-based IM/DD system is the waveform distortions induced by the serious fiber chromatic dispersion in C-band. These waveform distortions are inherently nonlinear due to square-law detection of DD receiver and limit the maximum transmission distance over dispersive optical fiber. Volterra nonlinear equalizers (VNLEs) have received a great deal of attention due to their capability to compensate for nonlinear distortions[7]. However, the conventional VNLE has high implementation complexity, which makes the nonlinear equalizer based on it unsuitable for cost-sensitive IM/DD systems. Recently, several studies have been reported to reduce the implementation complexity of VNLE[8,9]. For example, some researchers replaced the square operation by the absolute value operation to reduce algorithm complexity[8]. In Ref.[9], the author generated a sparse VNLE by simplifying the third-order Volterra equalizer and optimized the *BER* of the DML-based transmission system.

Thus, to solve the ISI caused by the bandwidth limitation and CD and the waveform distortions induced by the square-law detection, we proposed a simplified Volterra-based decision feedback equalizer (Volterra-DFE). Using this equalizer, experiments demonstrate that the channel configured with 128 Gbit/s PAM4 signal can transmit over 2 km in a standard single mode fiber (SSMF). The experiment presented in this letter is based on a Mach-Zehnder-based system with 3-dB bandwidth

---

* This work has been supported by the China Southern Power Grid Science and Technology Project, Research on 230 MHz Iot Access Architecture for Deep Coverage of Power Edge Services and R&D of Key Communication Devices (No.036000KK52180036).

** E-mail: buptwyb@163.com

of 26 GHz. Results show that the algorithm complexity is greatly reduced by 55%, while the sensitivity is reduced by 2 dBm compared with traditional feedforward equalization (FFE).

Digital signal processing (DSP) plays an important role in realizing an bandwidth-limited IM/DD system[10]. The DSP at the transmitter is mainly digital pre-compensation to solve the problem of bandwidth limitation[11], and the DSP at the receiver is mainly VNLE to solve the remaining linear and nonlinear damage of the system. We combine the nonlinear equalizer with decision feedback equalization (DFE) algorithm to better solve the problem of dispersion. Besides, simplification is done to reduce the complexity of the equalizer.

In our experiment, the Nyquist bandwidth of the PAM4 signal is 64 Gbit/s, which is much higher than the 3-dB bandwidth of our system. Thus we consider to use a pre-compensation in transmitter DSP to alleviate the bandwidth limitation. When the system bandwidth is severely limited, the time-domain equalization placed at the receiver will not only enhance the noise component in the high-frequency region, but also fail to accurately compensate the bandwidth. Considering the limited bandwidth and noise, the time domain pre-equalization is placed in the transmitter to compensate the system bandwidth. The impulse response of the time-domain pre-equalization structure can be expressed as

$$y_n = \sum_{k=1}^{L} w_k x_{n-k}, \tag{1}$$

where y_n and x_n respectively represent the output and input data sequences of the time domain pre-equalization, which has totally L taps. The key to realize time domain pre-equalization is to gain the tap coefficients which can be obtained by back-to-back (B2B) transmission in the same optical fiber communication system. The process is shown in Fig.1. Firstly, the transmitter generates a training sequence without pre-equalization. After B2B transmission, the training sequence is equalized at the receiver. Similar to the least mean square (LMS) algorithm, the goal of training is to use the least square algorithm to make the error signal $e(n)$ constantly decrease and make the equalization converge. Finally, the FFE tap coefficient can be used as the pre-equalization tap coefficient in the transmitter.

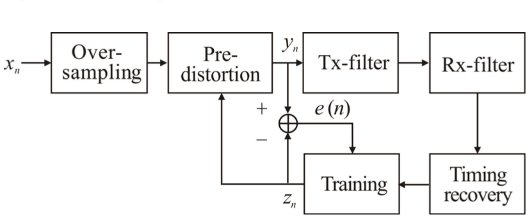

Fig.1 Process of time domain pre-equalization

In an IM/DD-based PAM4 transmission system, we can categorize the signal distortions mainly in three factors, namely, limited 3-dB bandwidth of devices, signal-to-signal beating noise (SSBN), and fiber nonlinearities. We can use a VNLE to simultaneously compensate the degradation of the signal in the receiver DSP[12,13]. The output signals of the third-order VNLE are expressed as[14]

$$\begin{aligned} y(k) = & \sum\nolimits_{l_1=0}^{L_1-1} h_1(l_1)x(k-l_1) + \\ & \sum\nolimits_{l_1=0}^{L_2-1}\sum\nolimits_{l_2=0}^{l_1} h_2(l_1,l_2)\prod\nolimits_{m=1}^{2} x(k-l_m) + \\ & \sum\nolimits_{l_1=0}^{L_3-1}\sum\nolimits_{l_2=0}^{l_1}\sum\nolimits_{l_3=0}^{l_2} h_3(l_1,l_2,l_3)\prod\nolimits_{m=1}^{3} x(k-l_m), \end{aligned} \tag{2}$$

where $x(k)$ is the input signal, $h_1(l_1)$, $h_2(l_1, l_2)$ and $h_3(l_1, l_2, l_3)$ respectively represent the first, second and third Volterra kernels, and L_1, L_2 and L_3 represent memory lengths in each part. It is worth noting that the first, second and third terms in Eq.(2) can respectively deal with the linear distortions, SSBN, and fiber nonlinearities. The total numbers of the three kernels are L_1, $L_2\times(L_2+1)/2$ and $L_3\times(L_3+1)\times(L_3+2)/6$, which means that the second and third kernels mainly determine the computational complexity in a VNLE. However, in the short-range IM-DD communication system, the nonlinear effect of optical fiber has little damage to the signal, and the nonlinear damage to the signal is mainly the SSBN and the fiber dispersion. In order to control the complexity of the equalizer, Volterra algorithm is only reserved to the second order. The structure of the second-order Volterra-DFE can be expressed as

$$\begin{aligned} y(n) = & \sum_{l_1=0}^{L_1-1} h_1(l_1)x(n-l_1) + \\ & \sum_{l_1=0}^{L_2-1}\sum_{l_2=0}^{l_1} h_2(l_1,l_2)x(n-l_1)x(n-l_2) + \\ & \sum_{k_1=1}^{K_1} g_1(k_1)y'(n-k_1) + \\ & \sum_{k_1=1}^{K_1}\sum_{k_2=1}^{K_2} g_2(k_1,k_2)y'(n-k_1)y'(n-k_2), \end{aligned} \tag{3}$$

where $g_1(k_1)$ and $g_2(k_1, k_2)$ respectively represent the first and second order kernel coefficients of DFE. To further simplify the equalizer, the second order kernels far from the main diagonal can be set to 0 and only the square terms are retained, thus reducing the number of taps. Besides, in MZM-based IM-DD system, the receiver performs square detection and the received signal is a real signal[15]. Thus the square operation of the second-order kernels can be converted into a relatively simple absolute operation, changing the second-order equalizer into a first-order equalizer. The structure of the proposed simplified second-order Volterra-DFE equalizer can be expressed as

$$\begin{aligned} y(n) = & \sum_{l_1=0}^{L_1-1} h_1(l_1)x(n-l_1) + \sum_{l_2=0}^{L_2-1} h_2(l_2)\left|x(n-l_2)\right| + \\ & \sum_{k_1=1}^{K_1} g_1(k_1)y'(n-k_1) + \sum_{k_2=1}^{K_2} g_2(k_2)\left|y'(n-k_2)\right|. \end{aligned} \tag{4}$$

The experimental setup for the 128 Gbit/s PAM4 signal transmission is shown in Fig.2. In the transmitter DSP, pulse shaping is first implemented on a PAM4 sequence (length: 65 536 symbols), 3% of which will be extracted as the training sequence for our equalization in receiver DSP. We choose different roll off factors in the B2B experiment and select the best one. Then, we execute a pre-compensation in the time domain to alleviate the distortions brought by device bandwidth deficiencies, in which the taps have been pre-measured after B2B transmission. Following the resample of the signal is completed before being sent to an arbitrary waveform generator (AWG) with a 92 GSa/s resampling rate. The electrical signal exported by AWG is amplified by a radio frequency (RF) driver whose 3-dB bandwidth is about 40 kHz—40 GHz and then modulated by a 1 550 nm-MZM with a 3-dB bandwidth of 30 GHz.

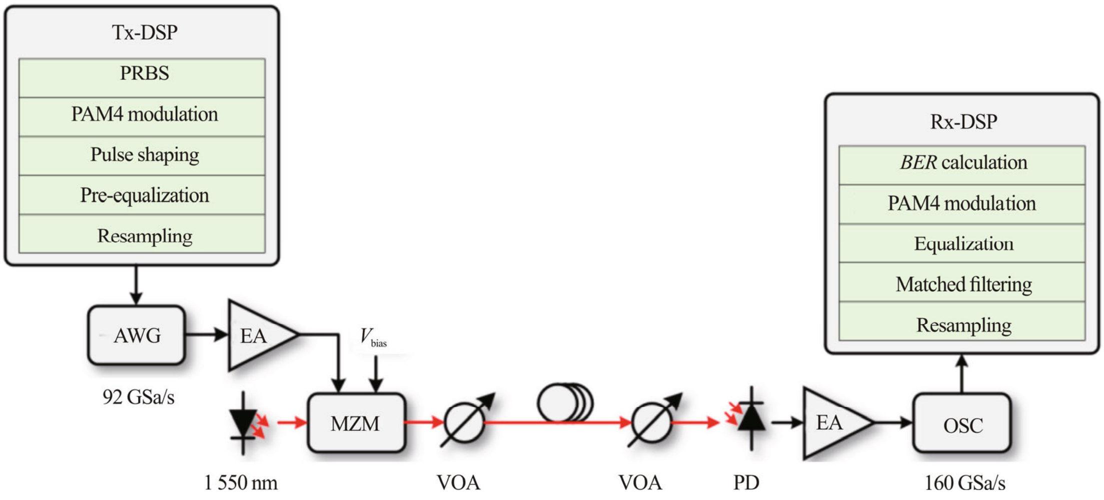

Fig.2 Experimental setup for 128 Gbit/s PAM4 signal

After the fiber transmission, we use a variable optical attenuator (VOA) to adjust the received power to study *BER* versus optical power. The optical signal is then detected by a 40 GHz-bandwidth pin-photodiode (no TIA) and amplified by an amplifier before being received by an oscilloscope with 160 GSa/s sampling rate. In the receiver offline DSP, we resample the data to two samples per symbol and complete matched filtering before equalization. Our proposed Volterra-DFE is then applied to equalize the PAM4 signal adaptively. Finally, PAM4 de-mapping and *BER* calculation of the signal are done whereafter.

In the following, we analyze the transmission performance of the 128 Gbit/s PAM4 signal. We first study the effect of transmitter pre-equalization. Fig.3 demonstrates comparison in *BER* versus received power with or without pre-equalization. We can see that pre-equalization slightly improves the *BER* after B2B transmission. However, when transmitting along 2 km SSMF, pre-equalization greatly improves the performance in *BER*. Without pre-equalization, the *BER* cannot reach 1×10^{-2}. With pre-equalization, the *BER* can be achieved at hard decision-forward error correction (HD-FEC) (*BER*=3.8×10^{-3}) with the received power of −3 dBm. So the effect of the provided algorithm is obvious. Influence of the taps number of pre-equalization is shown in Fig.4. After finding a balance between the equalization effect and complexity, 31 taps of time domain pre-equalization are selected.

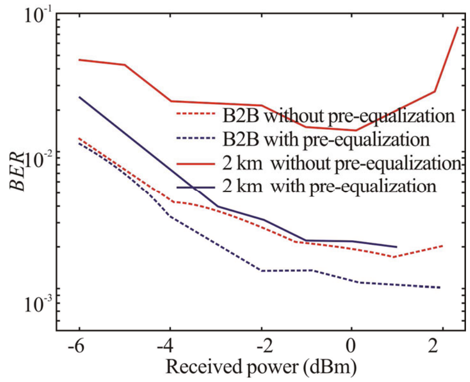

Fig.3 Comparison of *BER* versus received power with and without pre-equalization

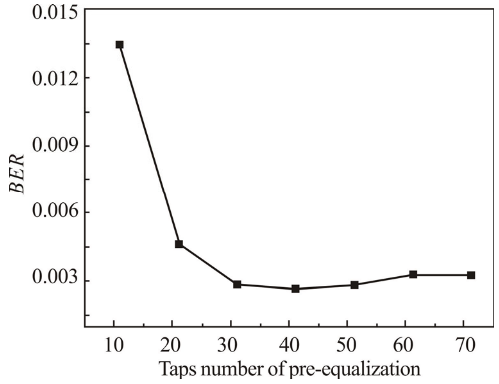

Fig.4 Relationship between *BER* and taps number of pre-equalization

Fig.5 and Fig.6 demonstrate the transmission performance after B2B or 2 km SSMF transmission. After B2B transmission, the number of taps in FFE is 31. There are 31 and 45 first-order and second-order taps in the feedforward part of Volterra-DFE, and 17 and 10 taps in the feedback part, respectively. In the meantime, the number of taps in our proposed simplified Volterra-DFE consists of 31 and 9 in feedforward parts while 17 and 5 in feedback parts. The total number of taps turns from 103 to 62 after simplification of the Volterra-DFE equalizer. We can see that the equalization effect of traditional Volterra-DFE is almost the same as that of simplified Volterra-DFE, though the optimization is not obvious compared with traditional FFE equalizer. The reason can be attributed to the small signal damage in B2B transmission, in which the main signal damage is the device bandwidth limitation, so that FFE equalizer is enough to equalize the signal.

After 2 km SSMF transmission, the number of taps in FFE equalizer is 41. There are 41 and 91 first-order and second-order taps in the feedforward part of Volterra-DFE, and 21 and 28 taps in the feedback part, respectively. In the meantime, the number of taps in our proposed simplified Volterra-DFE consists of 41 and 13 in feedforward parts while 21 and 7 in feedback parts. The total number of taps turns from 181 to 82 after simplification of the Volterra-DFE equalizer, which is reduced by 55%. The equalization effect of the proposed simplified Volterra-DFE is close to that of the traditional Volterra-DFE, while the computational complexity is reduced to a great extent, which means our simplification is reasonable and effective. In Fig.6, the simplified Volterra-DFE reaches the threshold of HD-FEC ($BER=3.8\times10^{-3}$) when received power is −4 dBm, which has an improvement of 2 dBm in sensitivity compared with traditional FFE equalizer.

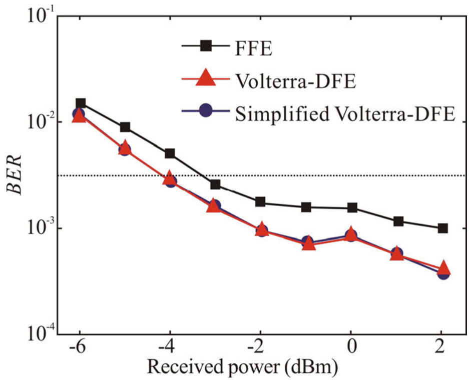

Fig.5 *BER* versus received power after B2B transmission

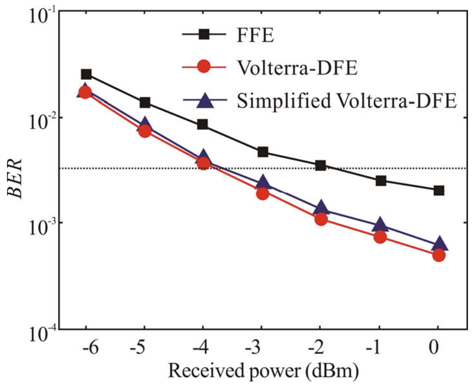

Fig.6 *BER* versus received power after 2 km SSMF transmission

In this paper, we simplify the structure of Volterra equalizer and reduce the order of equalizer from three to two by using absolute value operation instead of square operation. Based on the simplification, we propose a DFE algorithm combined with second-order Volterra nonlinear structure. Furthermore, in our experiment, we have demonstrated a single channel 128 Gbit/s transmission based on PAM4 signals. The signal distortions in the transmission are largely compensated by the time-domain pre-equalization and our proposed equalization. It provides an effective and low complexity choice for signal equalization in MZM-IMDD system in data communication.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

References

[1] CHAGNON M. Optical communications for short reach[J]. Journal of lightwave technology, 2019, 37(8)：1779-1797.

[2] ZHONG K P, ZHOU X, HUO J H, et al. Digital signal processing for short-reach optical communications：a review of current technologies and future trends[J]. Journal of lightwave technology, 2018, 36(2)：1-1.

[3] ZHANG K, ZHUGE Q B, XIN H Y, et al. Performance comparison of DML, EML and MZM in dispersion-unmanaged short reach transmissions with digital signal processing[J]. Optics express, 2018, 26(26)：34288-34304.

[4] HU Q, SCHUH K, CHAGNON M, et al. 84 GBd faster-than-Nyquist PAM-4 transmission using only linear equalizer at receiver[C]//2019 Optical Fiber Communications Conference and Exhibition, March 3-7, 2019, San Diego, California, USA. Washington：Optical Society of America, 2019：W4I.2.

[5] BO T W, KIM H. Coherent versus Kramers-Kronig transceivers in metro applications：a power consumption perspective[C]//2019 Optical Fiber Communications Conference and Exhibition, March 3-7, 2019, San Diego, California, USA. Washington：Optical Society of America, 2019：M1H.7.

[6] LAVRENCIK J, SIMPANEN E, HAGHIGHI N, et al. Error-free 850nm to 1060nm VCSEL links：feasibility of 400Gbps and 800Gbps 8λ-SWDM[C]//45th European Conference on Optical Communication, Septem-

ber 22-26, 2019, Dublin, Ireland. London：IET, 2019：1-4.

[7] ZHANG J, YE T P, YI X W, et al. An efficient hybrid equalizer for 50 Gb/s PAM-4 signal transmission over 50 km SSMF in a 10-GHz DML-based IM/DD system[C]//2017 Conference on Lasers and Electro-Optics (CLEO), May 14-19, 2017, San Jose, California, USA. New York：IEEE, 2017：17311263.

[8] YU Y K, BO T W, CHE Y, et al. Low-complexity nonlinear equalizer based on absolute operation for C-band IM/DD systems[J]. Optics express, 2020, 28(13)：19617-19628.

[9] CHEN Y B, WANG Y, LI W, et al. 106 Gbit/s PAM4 transmission employing a 15 GHz directly modulated laser[C]//2021 Asia Communications and Photonics Conference (ACP), October 24-27, 2021, Shanghai, China. New York：IEEE, 2021：21680633.

[10] ZHONG K P, ZHOU X, GUI T, et al. Experimental study of PAM-4, CAP-16, and DMT for 100 Gb/s short reach optical transmission systems[J]. Optics express, 2015, 23(2)：1176-1189.

[11] ZHANG J, YU J, ZHAO L, et al. Demonstration of 260-Gb/s single-lane EML-based PS-PAM-8 IM/DD for datacenter interconnect[C]//2019 Optical Fiber Communications Conference and Exhibition, March 3-7, 2019, San Diego, California, USA. Washington：Optical Society of America, 2019：W4I.4.

[12] BATISTA E L O, SEARA R. On the performance of adaptive pruned Volterra filters[J]. Signal processing, 2013, 93(7)：1909-1920.

[13] YU Y, CHOI M R, BO T, et al. Low-complexity 2nd-order Volterra equalizer for DML-based IM/DD transmission system[J]. Journal of lightwave technology, 2022, 38(7)：1735-1746.

[14] CHEN H Y, WEI C C, CHU H H, et al. An EAM-based 50-Gbps 60-km OFDM system with 29-dB loss budget enabled by SSII cancellation or Volterra filter[C]//2014 The European Conference on Optical Communication, September 21-25, 2014, Cannes, France. New York：IEEE, 2014：14768131.

[15] YU Y, CHOI M R, BO T, et al. Nonlinear equalizer based on absolute operation for IM/DD system using DML[J]. IEEE photonics technology letters, 2020, 32(7)：426-429.