A nonlinear equalization for a PAM4 IM/DD system using MZM*

LI Li, LIU Ran, and SUN Yadong**
College of Communication Engineering, Jilin University, Changchun 130012, China

(Received 19 October 2021)

The nonlinear distortion caused by the Mach-Zehnder modulator (MZM) is one of the main limiting factors for the improvement of the transmission performance of the intensity modulation and direct detection (IM/DD) optical communication system. In order to solve the problem, an improved Volterra nonlinear equalization (VNLE) method is proposed. Compared with the traditional VNLE that uses the least mean square (LMS) to calculate the tap coefficients, the improved VNLE uses the least square (LS) method to obtain more stable convergence. The simulation results show that the VNLE based on LS has better performance when solving complex nonlinear damage. For 25 Gbaud 4-level pulse amplitude modulation (PAM4) signals, the improved VNLE can reduce the bit error rate (*BER*) to below 10^{-4} in a 7-km-long single-mode optical fiber transmission system. In addition, in order to make the *BER* below 10^{-3}, the transmission distance that the improved VNLE can withstand is about 1.5 km longer than that of the traditional VNLE.
Document code: A **Article ID:** 1673-1905(2022)04-0238-5
DOI https://doi.org/10.1007/s11801-022-1165-z

In recent years, the demand for optical high-speed interconnection has been increasing driven by high-bandwidth internet applications, such as video streaming and cloud computing. Most data traffic occurs inside the data center, and the link length is up to 2 km. The requirements for these links are with low cost and complexity. In order to support the growth of optical data center interconnection and access network traffic, while meeting the stringent requirements of low cost, high energy efficiency and small size, intensity modulation and direct detection (IM/DD) communication systems, such as 4-level pulse amplitude modulation (PAM4), have been greatly developed. Compared with phase modulation schemes, they can reduce the cost and complexity of the transceiver[1-3]. However, compared with the optical communication system that transmits non-return-to-zero (NRZ) signals, the PAM4 system requires a higher signal-to-noise ratio and is more sensitive to inter-symbol interference (ISI) and nonlinear distortion[4-7].

Compared with the internal modulation using directly modulated laser (DML), the external modulation technology using Mach-Zehnder modulator (MZM) is favored due to low dispersion loss and higher modulation bandwidth. However, since the modulation curve of MZM cannot be completely regarded as a straight line, nonlinear distortion is inevitably introduced when modulating PAM4 signals. This problem seriously restricts the long-distance transmission of PAM4 signals.

Currently, researchers have considered several digital nonlinear equalization (NLE) techniques for nonlinear distortion compensation. One of the most popular NLE technologies in the field of digital signal processing (DSP) is to use a Volterra nonlinear equalizer (VNLE) because it can model complex nonlinear functions. Although VNLE successfully compensates most nonlinear distortions, they usually require high computational complexity[8-10]. The least mean square (LMS) algorithm is one of the most popular algorithms used to converge the tap coefficients of a VNLE. However, as the data rate and modulation order increase, LMS-based VNLE requires a large number of tap coefficients and training symbols. In this case, the LMS-based VNLE has the disadvantages of slow convergence, instability, and high mean square error. In order to improve the shortcomings of VNLE, scholars have proposed many improvements to improve the performance of VNLE[11-13].

In this article, the main focus of our work is to reduce the nonlinear damage caused by MZM during PAM4 signal transmission. This paper proposes a VNLE based on the least square (LS) method to calculate the tap coefficients as an improvement to the traditional VNLE. Compared with LMS, LS is more stable when calculating complex tap coefficients, and it can obtain global optimal tap coefficients without falling into local optimal tap coefficients. In this work, a fiber IM/DD communication simulation system based on 50 Gbit/s PAM4 was constructed by software of VPI, and the feasibility of the improved VNLE to compensate the nonlinear distortion

* This work has been supported by the National Key Technology and Development Project of China (No.2018YFB2201500).
** E-mail: LL@jlu.edu.cn

caused by MZM was verified. The research results indicate that the improved VNLE has better bit error rate (*BER*) performance, and compared with the traditional VNLE, it can achieve more stable and lower error convergence.

Volterra filters can be effectively used to simulate the distortion of semiconductor lasers, the transfer function of single-mode fibers, and the nonlinear propagation in multimode interference couplers. In direct detection systems, scholars have also proposed using it to compensate for nonlinear effects. The third-order Volterra expansion is as follows

$$y(n)=\sum_{k=0}^{N-1} w_k^{(1)} x_{n-k} + \sum_{k=0}^{N-1}\sum_{l=0}^{k} w_{k,l}^{(2)} x_{n-k}x_{n-l} + \sum_{k=1}^{N-1}\sum_{l=0}^{k}\sum_{m=0}^{l} w_{k,l,m}^{(3)} x_{n-k}x_{n-l}x_{n-m}, \quad (1)$$

where $w_k^{(1)}$, $w_{k,l}^{(2)}$ and $w_{k,l,m}^{(3)}$ are the first-order, the second-order and the third-order filter coefficients of VNLE, respectively. x is the input of the filter, y is the output of the filter, and N is the tap length of the first-order filter.

Compared to linear filters, VNLE expands the multiplicity of its high order multiplication. Each polynomial has a filter coefficient corresponding to it. With the increase of the VNLE orders, the number of polynomials will increase, which greatly increases the difficulty of implementation. Therefore, only low-order VNLE is considered in the actual system. In the IM/DD communication systems, limited three-order VNLE is sufficient to compensate for electron and optical linearity and nonlinear damage.

The VNLE filter coefficient usually uses the LMS algorithm iteration update. It provides a mathematical framework on how to adjust tap coefficients. However, since the autocorrelation matrix $\boldsymbol{R}_{xx}$ of input x is not diagonalized, and the eigenvalue spread is large, the filter convergence can be very slow with multiple local minima. The LMS algorithm is shown below

$$\boldsymbol{W}(m+1)=\boldsymbol{W}(m)+\mu\boldsymbol{e}_m\boldsymbol{X}(m), \quad (2)$$

$$\boldsymbol{e}_m=\hat{\boldsymbol{X}}(m)-\boldsymbol{W}(m)\boldsymbol{X}(m), \quad (3)$$

where μ is algorithm step size, $\boldsymbol{e}_m$ is error, $\hat{\boldsymbol{X}}(m)$ is expectation of the input filter $\boldsymbol{X}(m)$. In order to get the best filter coefficient matrix, we send a training sequence, $\hat{\boldsymbol{X}}(m)$ is determined by the training sequence. Because it is a third-order filter, the calculation of the filter coefficient matrix $\boldsymbol{W}(m)$ is much more complicated than that of a first-order linear filter.

The derivation process of the least square method is as follows, suppose the loss function $\boldsymbol{J}(\boldsymbol{W})$, and the optimal filter coefficient matrix $\boldsymbol{W}$ required should minimize the loss function as

$$\boldsymbol{J}(\boldsymbol{W})=[\hat{\boldsymbol{X}}-\boldsymbol{W}\boldsymbol{X}]^2=[\hat{\boldsymbol{X}}-\boldsymbol{W}\boldsymbol{X}]^{\mathrm{T}}[\hat{\boldsymbol{X}}-\boldsymbol{W}\boldsymbol{X}]. \quad (4)$$

When the derivative of $\boldsymbol{J}(\boldsymbol{W})$ is zero, $\boldsymbol{J}(\boldsymbol{W})$ takes the minimum value as

$$\frac{\partial \boldsymbol{J}(\boldsymbol{W})}{\partial \boldsymbol{W}}=2\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X}\boldsymbol{W}-2\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y}=0. \quad (5)$$

The filter coefficient matrix is

$$\boldsymbol{W}=(\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X})^{-1}\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y}. \quad (6)$$

According to the third-order Volterra expansion of Eq.(1), $\boldsymbol{X}$ is the sum of all polynomials, and $\boldsymbol{Y}$ is expectation of filter output value. $\boldsymbol{X}$ and $\boldsymbol{Y}$ are shown as

$$\boldsymbol{X}=\begin{bmatrix} x_3 & \cdots & x_n \\ x_2 & & x_{n-1} \\ x_1 & & x_{n-2} \\ x_3^2 & & x_n^2 \\ x_3x_2 & \cdots & x_nx_{n-1} \\ \vdots & & \vdots \\ x_2^2 & & x_{n-1}^2 \\ \vdots & & \vdots \\ x_3^3 & \cdots & x_n^3 \\ x_3^2x_2 & & x_n^2x_{n-1} \\ \vdots & & \vdots \\ \vdots & & \vdots \end{bmatrix}^{\mathrm{T}}, \quad (7)$$

$$\boldsymbol{Y}=[y_1,y_2,y_3,......y_M]. \quad (8)$$

According to Eqs.(6)—(8), the optimal solution of $\boldsymbol{W}$ can be obtained.

This part shows the 50 Gbit/s PAM4 IM/DD communication simulation system built by VPI, and compares the performance of three algorithms based on LMS linear equalizer, traditional VNLE and improved VNLE.

The modulation curve of MZM can be regarded as $P_{\mathrm{out}}(t)=P_{in}(t)\cdot\cos^2[\Delta\phi(t)]$ when the output signal has a peak to average power ratio (*PAPR*). MZM will work in the nonlinear region of the modulation curve, which makes the eye opening of the modulated PAM4 signal vary. This nonlinear distortion is the main source of nonlinear damage in the transmission process of PAM4 signal. In the simulation system, we set the maximum to minimum peak power ratio of the output MZM signal to be 20 dB. In this case, the middle eye of the eye diagram of PAM4 will be widened, and the upper and lower eyes will shrink, which will cause large nonlinear damage under the dispersion interaction with the fiber.

Fig.1 shows block diagram of 50 Gbit/s optical PAM4 system for short-reach optical interconnects. MATLAB generates PAM4 digital code. The generated PAM4 digital signal is resampled to two samples per symbol and then uploaded to a digital-to-analog converter (DAC) with 50 GSa/s sampling rate and 20 GHz bandwidth. Thus, the generated electrical PAM4 signal has a baud rate of 25 Gbaud. After that, the PAM4 electrical signal is modulated on a 1 310 nm continuous wave optical carrier by an MZM. The laser optical power is set to 10 mW. The modulated optical signal enters the 10-km-long single-mode fiber.

The single-mode fiber uses the UniversalFiber module in the VPI. The fiber optic module is a simplified version of the general fiber optic module. It can be used to simulate the transmission of broadband nonlinear signals in optical fibers. Single-mode fiber parameters are shown in Tab.1.

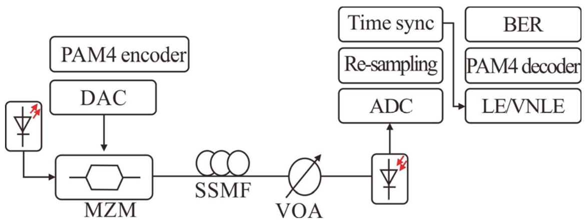

Fig.1 Block diagram of 50 Gbit/s optical PAM4 system for short-reach optical interconnects

Tab.1 Parameters for simulation

Parameter	Value
Fiber length	10 km
Fiber loss	0.2 dB/km
Dispersion	16×10^{-6} s/m^2
Nonlinear index	2.6×10^{-20} m^2/W
Group refractive index	1.47

At the receiver, a variable optical attenuator (VOA) is used to adjust the received optical power. The light signal is converted into an electrical signal by a PIN photodetector. The electrical signal is fed into a 50 GSa/s real-time analog-to-digital converter (ADC) with a bandwidth of 25 GHz to achieve analog-to-digital conversion. The digital PAM4 signal is decoded through offline processing, including resampling, clock synchronization, equalization algorithm, PAM4 symbol to bit demapper, and *BER* calculation. Set the training sequence length to 3 000.

The most commonly used method for VNLE to calculate tap coefficients is LMS. Therefore, when comparing algorithms, we choose the LMS-based VNLE as the representative of the traditional nonlinear equalizer. Fig.2 shows the eye diagram of the PAM4 signal after 10 km transmission.

Fig.3 shows the relationship between transmission distance and *BER* in three cases, unbalanced, after linear equalizer equalization, and after classic VNLE equalization. Change the transmission distance and conduct multiple experiments. The laser transmission power is set to 10 mW, and the transmission distance is set to 6.0 km, 7.0 km, 7.5 km, 8.0 km, 8.5 km, 9.0 km, and 10.0 km in sequence. We found that the compensation effect of nonlinear equalization on the signal is improved by an order of magnitude compared with linear equalization. This shows that the signal has suffered a certain degree of nonlinear damage during transmission, and it is necessary to use VNLE for signal compensation.

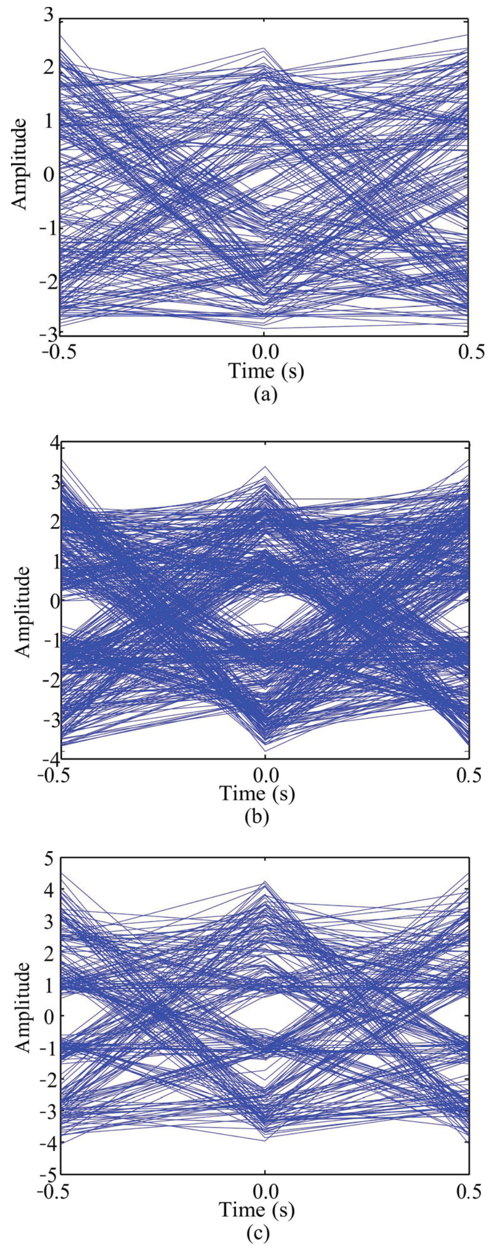

Fig.2 50 Gbit/s PAM4 signal transmission experimental results: (a) Eye diagram without equalizer; (b) Eye diagram after linear equalization algorithm; (c) Eye diagram after traditional VNLE

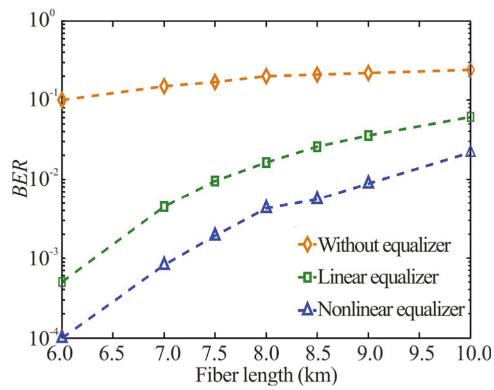

Fig.3 Simulation results for 50 Gbit/s PAM4 transmission over SSMF with different lengths

Because VNLE has a large number of tap coefficients, VNLE based on LS is used as a solution to improve VNLE. As shown in Fig.4, the performance of the three algorithms of linear equalizer, traditional VNLE and improved VNLE are compared. The simulation results show that when the transmission fiber distance is 6 km, the error rate of the improved VNLE can reach below 10^{-5}. In order to make the *BER* reach 10^{-3}, the acceptable transmission distance of the improved VNLE is about 1.5 km longer than the traditional VNLE and about 2 km longer than the linear equalization.

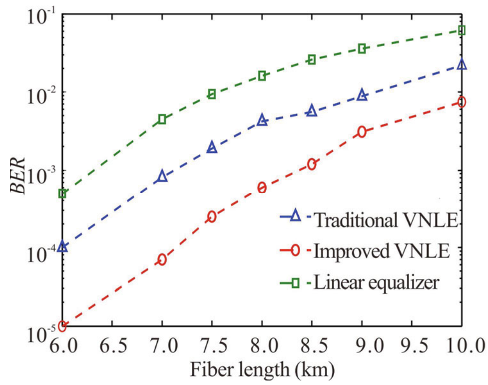

Fig.4 Comparison of different approaches for 50 Gbit/s PAM4 transmission over SSMF with different lengths

Next, we compare the performance of the three algorithms of the improved VNLE, the traditional VNLE, and the linear equalizer under the same transmission distance. Fig.5 shows the relationship between the *BER* of the three algorithms and the received optical power when the transmission distance is 7 km.

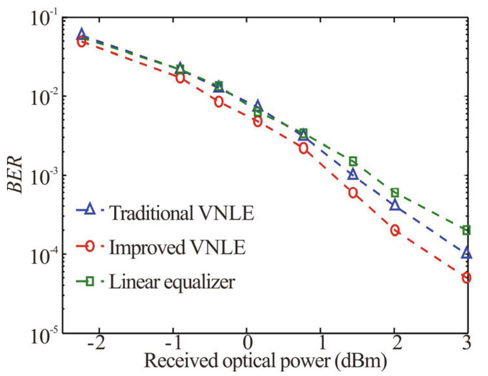

Fig.5 Comparison of different approaches for 50 Gbit/s PAM4 transmission over 7-km-long SSMF

It can be seen from Fig.5 that when the received optical power is low, the received signal is greatly affected by noise, and the performance of the three algorithms is similar. As the received optical power increases to 1 dBm, the factor that has the greatest influence on the signal gradually turns into crosstalk between symbols. Under these circumstances, it can be found that the improved VNLE is significantly better than the other two, and the linear equalization performance is not as good as the nonlinear equalization. To achieve a *BER* of 10^{-4}, the improved VNLE requires about 0.5 dBm lower received power than the traditional VNLE.

In this article, in order to deal with the nonlinear signal distortion caused by MZM in the IM/DD transmission system, a theoretical analysis of VNLE is provided. Aiming at the situation that the equalizer based on Volterra series has too many tap coefficients and it is difficult to converge, this paper proposes an improved scheme based on the LS method to calculate the tap coefficients. The simulation results show that the improved VNLE can significantly reduce the nonlinear distortion of the system. The equalized *BER* can be reduced to below 10^{-4} when the 25 Gbaud PAM4 transmits 7 km. The feasibility of the improved VNLE to compensate the nonlinear distortion caused by MZM is proved. In short, in the future optical fiber link transmission system between data centers, PAM4 has great potential for development.

Statements and Declarations

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

References

[1] WEI J L, ZHANG L, PRODANIUC C, et al. Linear pre-equalization techniques for short reach single lambda 225 Gb/s PAM IMDD systems[C]//2018 European Conference on Optical Communication, September 23-27, 2018, Rome, Italy. New York：IEEE, 2018：8535347.

[2] FIKY E E, CHAGNON M, SOWAILEM M, et al. 168-Gb/s single carrier PAM4 transmission for intra-data center optical interconnects[J]. IEEE photonics technology letters, 2017, 29(3)：314-317.

[3] EISELT N, MUENCH D, DOCHAN A, et al. Performance comparison of 112-Gb/s DMT, Nyquist PAM4, and partial-response PAM4 for future 5G ethernet-based fronthaul architecture[J]. Journal of lightwave technology, 2018, 36(10)：1807-1814.

[4] WAN Z, LI J, SHU L, et al. 64-Gb/s SSB-PAM4 transmission over 120-km dispersion-uncompensated SSMF with blind nonlinear equalization, adaptive noise-whitening postfilter and MLSD[J]. Journal of lightwave technology, 2017, 35(23)：5193-5200.

[5] HAGER C, PFISTER H. Nonlinear interference mitigation via deep neural networks[C]//Optical Fiber Communication Conference, March 11-15, 2018, San Diego, CA, USA. Washington：Optical Society of America, 2018：17856365.

[6] ZHOU J, QIAO Y, HUANG X, et al. Joint FDE and MLSD algorithm for 56-Gbit/s optical FTN-PAM4 system using 10G-class optics[J]. Journal of lightwave technology, 2019, 37(13)：3343-3350.

[7] FU P C, YU F S, CHEN L, et al. Study on RZ-4PAM

downstream signals with duty cycles of 33% and 50% for optical access system application[J]. Optoelectronics letters, 2017, 13(1): 63-66.

[8] ZHONG K P, ZHOU X, TAN G, 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: 1176-1188.

[9] LYUBOMIRSKY I, LING W A. Advanced modulation for datacenter interconnect[C]//2016 Optical Fiber Communications Conference and Exhibition, March 20-24, 2016, Anaheim, California, USA. Washington: Optical Society of America, 2016: w4j3.

[10] STOJANOVIC N, QIANG Z, PRODANIUC C, et al. Performance and DSP complexity evaluation of a 112-Gbit/s PAM-4 transceiver employing a 25-GHz TOSA and ROSA[C]//2015 European Conference on Optical Communication, September 27 - October 1, 2015, Valencia, Spain. New York: IEEE, 2015: 15635970.

[11] KARINOU F, QIANG Z, PRODANIUC C. Volterra and Wiener equalizers for short-reach 100G PAM-4 applications[J]. Journal of lightwave technology, 2017, 35(21): 4583-4594.

[12] DIAMANTOPOULOS N, NISHI H, KOBAYASHI W, et al. On the complexity reduction of the second-order Volterra nonlinear equalizer for IM/DD systems[J]. Journal of lightwave technology, 2019, 37(4): 1214-1224.

[13] GU Q Q, LV S S, JIANG M S, et al. Phase error correction method based on the Gaussian filtering algorithm and intensity variance[J]. Optoelectronics letters, 2021, 17(4): 221-225.