Compensation of optical nonlinear waveform distortion using neural-network based digital signal processing

Shotaro Owaki and Moriya Nakamura^{a)}

School of Science and Technology, Meiji University,

1-1-1 Higashi-Mita, Tama-ku, Kawasaki-shi, Kanagawa 214-8571, Japan

a) m_naka@meiji.ac.jp

Abstract: We studied a novel nonlinear compensation scheme using digital signal processing based on a neural network (NN). Distortion of 16QAM signals caused by self-phase modulation (SPM) was compensated for by using a three-layer NN without feedback loops. In the scheme, the input layer of the NN has feedforward tapped delay lines. Input signals of I and Q components of the 16QAM signals are fed into the delay lines. The compensated 16QAM signals of the I and Q components are outputted by two neurons in the output layer of the NN. BER and EVM performance was investigated by numerical simulations, and the EVM was improved by more than 20% by the compensation.

Keywords: digital signal processing, nonlinear distortion, SPM, neural network

Classification: Fiber-Optic Transmission for Communications

References

- [1] M. Nakamura and Y. Kamio, “30-Gbps (5-Gsymbol/s) 64-QAM self-homodyne transmission over 60-km SSMF using phase-noise cancelling technique and ISI-suppression based on electronic digital processing,” *Optical Fiber Communication Conference (OFC2009)*, OWG4, Mar. 2009. DOI:10.1364/OFC.2009.OWG4
- [2] X. Chen, X. Liu, S. Chandrasekhar, B. Zhu, and R. W. Tkach, “Experimental demonstration of fiber nonlinearity mitigation using digital phase conjugation,” *Optical Fiber Communication Conference (OFC2012)*, OTh3C, Mar. 2012.
- [3] E. Ip and J. M. Kahn, “Compensation of dispersion and nonlinear impairments using digital backpropagation,” *J. Lightwave Technol.*, vol. 26, no. 20, pp. 3416–3425, Oct. 2008. DOI:10.1109/JLT.2008.927791
- [4] L. Zhu, F. Yaman, and G. Li, “Experimental demonstration of XPM compensation for WDM fibre transmission,” *Electron. Lett.*, vol. 46, no. 16, pp. 1140–1141, Aug. 2010. DOI:10.1049/el.2010.1444
- [5] L. Liu, L. Li, Y. Huang, K. Cui, Q. Xiong, F. N. Hauske, C. Xie, and Y. Cai, “Intrachannel nonlinearity compensation by inverse volterra series transfer function,” *J. Lightwave Technol.*, vol. 30, no. 3, pp. 310–316, Feb. 2012.

DOI:10.1109/JLT.2011.2182038

- [6] R. Zayani, R. Bouallegue, and D. Roviras, “Levenberg-Marquardt learning neural network for adaptive pre-distortion for time-varying HPA with memory in OFDM systems,” European Signal Processing Conference (EUSIPCO2008), L5-6-3, Aug. 2008.
- [7] P.-R. Chang and B.-C. Wang, “Adaptive decision feedback equalization for digital satellite channels using multilayer neural networks,” *IEEE J. Sel. Areas Commun.*, vol. 13, no. 2, pp. 316–324, Feb. 1995. DOI:10.1109/49.345876
- [8] S. Warm, C.-A. Bunge, T. Wuth, and K. Petermann, “Electronic dispersion precompensation with a 10-Gb/s directly modulated laser,” *IEEE Photonics Technol. Lett.*, vol. 21, no. 15, pp. 1090–1092, Aug. 2009. DOI:10.1109/LPT.2009.2022957
- [9] M. A. Jarajreh, E. Giacomidis, I. Aldaya, S. T. Le, A. Tsokanos, Z. Ghassemlooy, and N. J. Doran, “Artificial neural network nonlinear equalizer for coherent optical OFDM,” *IEEE Photonics Technol. Lett.*, vol. 27, no. 4, pp. 387–390, Feb. 2015. DOI:10.1109/LPT.2014.2375960
- [10] S. T. Ahmad and K. P. Kumar, “Radial basis function neural network nonlinear equalizer for 16-QAM coherent optical OFDM,” *IEEE Photon. Technol. Lett.*, vol. 28, no. 22, pp. 2507–2510, Nov. 2016. DOI:10.1109/LPT.2016.2601901
- [11] S. Owaki and M. Nakamura, “Equalization of optical nonlinear waveform distortion using neural-network based digital signal processing,” Optoelectronics and Communications Conference (OECC2016), WA2-40, Jul. 2016.
- [12] D. W. Marquardt, “An algorithm for least-squares estimation of nonlinear parameter,” *J. Soc. Ind. Appl. Math.*, vol. 11, no. 2, pp. 431–441, Jun. 1963. DOI:10.1137/0111030

1 Introduction

Multi-level modulation schemes are key technologies to accommodate the increasing data traffic on communication networks. In particular, quadrature amplitude modulation (QAM) is an important candidate for attaining modulation at higher than four bits per symbol. On the other hand, the waveforms of QAM signals are distorted by self-phase modulation (SPM), because the signal power varies according to the transmitted symbols, resulting in a large peak-to-average power ratio (PAPR). Finite impulse response (FIR) filters have been used to compensate for linear distortion caused by, e.g., chromatic dispersion [1], but they cannot be used to compensate for nonlinear distortion. Some methods have been proposed for compensating for nonlinear effects, including optical phase conjugation (OPC) [2], digital back propagation (DBP) [3, 4], and the Volterra series transfer function (VSTF) [5]. However, these methods need an enormous amount of calculations or additional optical/electronic hardware components. Digital signal processing based on neural networks (NNs) has the merit that NNs can adaptively compensate for nonlinear distortion by using supervised learning algorithms. Some methods to compensate for nonlinear effects in wireless communication systems have been studied [6, 7]. In optical communication systems, nonlinear distortion compensation using NNs has been conventionally studied for Intensity Modulation-Direct Detection (IM-DD) transmission systems [8]. Recently, nonlinear equalization using NNs in frequency domain was investigated for coherent optical orthogonal

frequency division multiplexing (CO-OFDM) transmission systems, where many sub-NNs were used for subcarriers [9, 10]. We proposed a novel nonlinear compensation method using an NN to compensate optical multi-level signals distorted by SPM [11]. We showed that the NN can effectively compensate for distortion of 16QAM optical signals caused by SPM. In that study, however, we used an NN including complicated feedback loops, which possibly destabilized the system performance. In the present study, we investigated the performance of a simple three-layer NN without feedback to compensate for nonlinear distortion caused by SPM. Numerical simulation of 16QAM transmission showed that the NN can compensate for the nonlinear distortion as efficiently as the case with feedback loops. We evaluated the performance in terms of bit error rate (BER) and error vector magnitude (EVM).

2 Nonlinear compensation using an NN

Fig. 1 shows the construction of the three-layer NN that we used in the nonlinear compensation. The input layer of the NN has feedforward tapped delay lines. Input signals of in-phase (I) and quadrature (Q) components are fed into the delay lines. Neurons in the hidden layer have a sigmoidal output function. The neurons in the input and output layers have linear functions.

Fig. 1. Construction of three-layer NN.

The neurons in the output layer output compensated signals described by

$$y = f\left(\sum_{k=1}^n w_k x_k + b\right), \quad (1)$$

where x_k is the input from k -th neuron, w_k is the weight, b is the bias, and f is the output function. The values of the weight and bias are calculated by the Back Propagation (BP) algorithm to minimize the error, e , which is defined as the difference between the output signals and supervised signals:

$$e^2 = \sum_{k=1}^n (y_i - d_i)^2, \quad (2)$$

where d_i is the supervised signal. In this simulation, the numbers of input-layer neurons for both I and Q components were set to 12. The numbers of neurons in the hidden and output layers were set to 6 and 2, respectively.

3 System setup

Fig. 2 shows a 50-km 16QAM signal transmission system used in our simulations. 10-Gsymbol/s 16QAM optical signal was modulated by PRBS $2^{20}-1$ data and transmitted by a standard single mode fiber (SSMF) and a dispersion compensation fiber (DCF) having a total length of 50 km, cancelling the chromatic dispersion. The input power to the optical fibers was 10 dBm. The noise figure of EDFAs were 3 dB. After the transmission, the optical signal was received by optical homodyne detection. Here, we assumed that the local oscillator (LO) was ideally synchronized to the optical signal. The optical power of the LO was 3 dBm. In the simulation, electrical noise was taken into account only at PDs as thermal noise with power density of 1.0×10^{-10} pW/Hz. Then, the distorted signal after the transmission was compensated using an NN in a digital signal processor (DSP). The sampled data were processed in 1-sample/symbol manner in the DSP consistently. The NN was trained using the Levenberg–Marquardt algorithm, which is a kind of BP [12]. We used random data sequence of about 50,000 symbols repeatedly for the training. The compensation performance was evaluated by BER and EVM.

Fig. 2. System setup of 16QAM transmission.

4 Result and discussion

Fig. 3(a) shows the constellation of the received 16QAM signal in a back-to-back (BtB) configuration when the received power was -10 dBm. Fig. 3(b) shows the constellation after the transmission. Due to the large input power, the outer symbols of 16QAM signals were rotated in the clockwise direction by SPM, and Fig. 3(c) shows the constellation after the compensation using an NN. The distorted symbols were successfully compensated. EVM was improved by about 24%. Next, we investigated the compensation performance in the case where the received power is limited by the attenuator (ATT). Fig. 3(d) shows the constellation of the received 16QAM signal in the BtB configuration when the received optical power was -32 dBm, and Fig. 3(e) shows the constellation after the transmission. Fig. 3(f) shows the constellation after the compensation using the NN. The EVM was improved by about 20%. However, we could not recover the original constellation shown in Figs. 3(a) and (d) completely by the equalization. We calculated the EVM and BER versus received optical power, which was adjusted by the attenuator at the receiver side. Fig. 3(g) shows the EVM and BER characteristics calculated in the simulation. An EVM of less than 10% was achieved when the received power was

higher than about 36 dBm, whereas the EVM without the compensation was about 30%. A BER of less than 10^{-6} was achieved by the compensation. In the figure, we also plotted EVM values in the case where an NN with feedback loops was employed as reported in [11]. However, no significant difference due to the feedback loops was observed. By removing the feedback loops, we can eliminate the possibility of unstable behavior and oscillation of the NN. In our simulations, the DSP was only used to calculate the equalization with the NN. In practical receivers, however, a DSP includes some functional blocks such as chromatic dispersion compensation, polarization demux, and carrier phase recovery. The nonlinear equalization can be used after all the linear processing and phase recovery. However, the best order in the processing sequence has to be investigated in the succeeding studies.

Fig. 3. Constellations and EVM/BER characteristics.

5 Conclusion

We investigated the compensation performance of a three-layer NN to compensate for nonlinear distortion in optical communication systems. Our numerical simulation of 16QAM transmission showed that the NN could efficiently compensate for the nonlinear distortion caused by SPM, and improved the performance in terms of BER and EVM.

© IEICE 2017

DOI: 10.1587/comex.2017XBL0078

Received April 27, 2017

Accepted May 17, 2017

Publicized May 31, 2017

Copyedited August 1, 2017