FWM compensation using artificial-neural-network-based digital signal processing and a phase-locked multicarrier source

Shotaro Owaki and Moriya Nakamura^{a)}

School of Science and Technology, Meiji University,

1-1-1 Higashimita, Tama-ku, Kawasaki, Kanagawa 214-8571, Japan

a) m_naka@meiji.ac.jp

Abstract: We propose a four-wave mixing (FWM) compensation scheme using artificial-neural-network (ANN)-based digital signal processing. A phase-locked multicarrier source was employed to assure the deterministic phase relation between the carriers. The ANN successfully compensated for not only self-phase modulation (SPM) and cross-phase modulation (XPM) but also the nonlinear waveform distortion caused by FWM in the phase-locked condition. We investigated the compensation performance using a transmission system involving 5-ch wavelength-division multiplexing (WDM) of 16QAM-signals by numerical simulations. The performance in terms of the error vector magnitude (EVM) was improved by more than 19% using the proposed compensation method.

Keywords: digital signal processing, nonlinear distortion, XPM, FWM, artificial neural network, phase-locked multicarrier

Classification: Fiber-Optic Transmission for Communications

References

- [1] 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
- [2] E. Mateo, L. Zhu, and G. Li, "Impact of XPM and FWM on the digital implementation of impairment compensation for WDM transmission using backward propagation," *Opt. Express*, vol. 16, no. 20, pp. 16124–16137, Sep. 2008. DOI:10.1364/OE.16.016124
- [3] 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
- [4] 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
- [5] S. Owaki and M. Nakamura, "XPM compensation in optical fiber transmission systems using neural-network-based digital signal processing," *IEICE*

- Commun. Express*, vol. 7, no. 1, pp. 31–36, Jan. 2018. DOI:10.1587/comex.2017XBL0149
- [6] D. E. Rumelhart, J. L. McClelland, and PDP Research Group, *Parallel Distributed Processing*, A Bradford Book, 1987.
 - [7] M. Schetzen, *The Volterra & Wiener Theories of Nonlinear Systems*, Krieger, 2006.
 - [8] T. Kyono, Y. Otsuka, Y. Fukumoto, S. Owaki, and M. Nakamura, “Computational-complexity comparison of artificial neural network and Volterra series transfer function for optical nonlinearity compensation with time- and frequency-domain dispersion equalization,” *European Conference on Optical Communication (ECOC2018)*, Th2.28, Sep. 2018. DOI:10.1109/ECOC.2018.8535153
 - [9] R. Zayani and R. Bouallegue, “Pre-distortion for the compensation of HPA nonlinearity with neural networks: Application to satellite communications,” *Int. J. Comput. Sci. Network Security*, vol. 7, no. 3, pp. 97–103, Mar. 2007.
 - [10] 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
 - [11] J. Estaran, R. Rios-Müller, M. A. Mestre, F. Jorge, H. Mardoyan, A. Konczykowska, J.-Y. Dupuy, and S. Bigo, “Artificial neural networks for linear and non-linear impairment mitigation in high-baudrate IM/DD systems,” *European Conference on Optical Communication (ECOC2016)*, M.2.B.2, Sep. 2016.
 - [12] 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
 - [13] 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.
 - [14] S. Owaki and M. Nakamura, “Compensation of optical nonlinear waveform distortion using neural-network based digital signal processing,” *IEICE Commun. Express*, vol. 6, no. 8, pp. 484–489, May 2017. DOI:10.1587/comex.2017XBL0078
 - [15] S. Owaki, Y. Fukumoto, T. Sakamoto, N. Yamamoto, and M. Nakamura, “Experimental demonstration of SPM compensation based on digital signal processing using a three-layer neural-network for 40-Gbit/s optical 16QAM signal,” *IEICE Commun. Express*, vol. 7, no. 1, pp. 13–18, Jan. 2018. DOI:10.1587/comex.2017XBL0148
 - [16] E. Yamazaki, F. Inuzuka, K. Yonenaga, A. Takada, and Y. Miyamoto, “Digital compensation of intercarrier nonlinear distortion with carrier phase locking,” *J. Lightwave Technol.*, vol. 28, no. 5, pp. 828–836, Mar. 2010. DOI:10.1109/JLT.2009.2033615
 - [17] Y. Fumumoto, S. Owaki, and M. Nakamura, “Effect of number of neurons of a neural-network on compensation performance of SPM non-linear waveform distortion,” *Optoelectronics and Communications Conference (OECC2017)*, P3-008, Aug. 2017. DOI:10.1109/OECC.2017.8114880
 - [18] T. A. Eriksson, H. Bülow, and A. Leven, “Applying neural networks in optical communication systems: Possible pitfalls,” *IEEE Photon. Technol. Lett.*, vol. 29, no. 23, pp. 2091–2094, Dec. 2017. DOI:10.1109/LPT.2017.2755663

1 Introduction

Wavelength division multiplexing (WDM) technology has been playing an important role in improving the transmission capacity and spectral efficiency of optical fibers. A key technology that can achieve further improvements is multi-level modulation, including quadrature amplitude modulation (QAM), which attains modulation at higher than four bits per symbol. However, the waveform of a QAM signal is distorted by nonlinear effects such as self-phase modulation (SPM), because the signal power varies according to the transmitted symbols, resulting in a large peak-to-average power ratio (PAPR). In particular, the signals are distorted by cross phase modulation (XPM) in WDM systems. Some methods have been proposed for compensating for nonlinear effects in WDM systems, including digital back propagation (DBP) [1, 2, 3] and the Volterra series transfer function (VSTF) [4]. However, these methods need an enormous amount of calculations. We have proposed using an artificial neural network (ANN) for the compensation of nonlinear waveform distortion caused by XPM [5]. The calculation cost of an ANN increases in proportion to the number of neurons in each layer, whereas that of the VSTF increases exponentially as the numbers of tapped delays and the order of the Volterra series increase [6, 7]. Recently, it was reported that the ANN has strong advantage of computational complexity compared with VSTF [8]. In the study, it was also reported that any significant difference of the compensation performance was not found between the ANN and the VSTF. Additionally, ANNs can adaptively compensate for nonlinear distortion by using supervised learning algorithms. In the past, ANNs have been investigated for compensating for nonlinear effects in wireless communication systems [9, 10]. In optical communication systems, ANNs have been used for single channel transmission [11, 12, 13, 14, 15]. To the best of the authors' knowledge, however, compensation of four-wave mixing (FWM) by ANNs has not been studied. In this paper, we propose and investigate a FWM compensation scheme based on an ANN. We employed a phase-locked multicarrier source to assure the deterministic phase relation between WDM carriers [16]. Numerical simulation of 5-ch WDM transmission of 16-ary QAM (16QAM) signals showed that the ANN could efficiently compensate for the effect of FWM. We evaluated the performance in terms of the error vector magnitude (EVM).

2 Construction of ANN

In the proposed compensation scheme, we assume a deterministic phase relation between WDM carriers by using a phase-locked multicarrier source. In this phase-locked condition, we can regard the effect of FWM as deterministic waveform distortion, which can be compensated for using a nonlinear operation [16]. Fig. 1 shows the construction of the three-layer ANN that we used in the FWM compensation. The input layer of the ANN has feedforward tapped delay lines. In-phase (I) and quadrature (Q) components of all the received WDM channels (ch. 1 to 5) are fed into the delay lines. The output layer has two neurons for I- and Q-components of only the intended channel (ch. 3) for simplicity. If we need to compensate other channels, the output layer has to have corresponding output

Fig. 1. Construction of ANN.

neurons. Even when the output layer has other neurons for multiple intended channels, however, the input and hidden layers are shared by these multiple channels. The hidden-layer neurons have a sigmoidal output function, whereas the input- and output-layer neurons have linear functions. The neurons output signals described by

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

where x_k is the input from the k -th neuron, w_k is the weight, b is the bias, f is the output function, and y_i is the output of the i -th neuron in the layer. The values of the weight and bias are calculated by the error back propagation (EBP) algorithm to minimize the error e [6], which is defined as the difference between the output signals and supervised signals:

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

where d_i is the supervised signal that is the known target for the i -th output-layer neuron. In this simulation, the numbers of input-layer neurons for each I- and Q-components of all the received channels were set to 10. (In total, 100 neurons for I- and Q-components of 5 channels.) The numbers of hidden- and output-layer neurons were set to 30 and 2, respectively. We set the number of neurons in the ANN based on our past investigation [17]. Then, we optimized the number of neurons, while observing the compensation performance. In the learning process, we used PRBS $2^{15} - 1$ data which is long enough compared with the size of input-layer neurons, to avoid overfitting and overestimation of the performance [18]. After the learning process, we also confirmed that any overfitting and overestimation did not occur by estimating the system using some other PRBS data with different orders.

3 System setup

Fig. 2 shows a 50-km 16QAM-signal WDM transmission system used in our simulation for FWM compensation. We used a laser diode (LD) with a frequency of

193.4 THz and a linewidth of 100 kHz. Two Mach-Zhender modulators (MZMs) were driven with a 50 GHz sine wave to realize phase-locked carriers having a 50 GHz frequency spacing. The five phase-locked carriers were WDM demultiplexed and modulated by 10-Gsymbol/s 16QAM using PRBS $2^{15} - 1$ data, individually. The WDM optical signals were transmitted by a dispersion-shifted fiber (DSF) having large fiber-optic nonlinearity. The loss and the dispersion at the wavelength of ch. 3 were 0.2 dB/km and -0.28 ps/nm/km, respectively. A_{eff} and n_2 were $50 \mu\text{m}^2$ and $2.6 \times 10^{-20} \text{ m}^2/\text{W}$, respectively. The total input power to the transmission line was 10 dBm. In the simulation, all the WDM channels had the same state of polarization to observe the distortion caused by XPM in the worst condition, because the effect of XPM becomes maximum when the states of polarization are the same. After the transmission, the WDM signals were demultiplexed. The intended channel (ch. 3) was attenuated using a variable optical attenuator (ATT) to observe the performance versus received optical power, and the 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. At the same time, the other optical signals on ch. 1, 2, 4, and 5 were detected by optical homodyne detection. All the received signals were fed into the ANN to compensate for the nonlinear effects including FWM on ch. 3.

Fig. 2. System setup of 16QAM-signal WDM transmission.

4 Results and discussion

First, we investigated the compensation performance in a case using individual LDs for ch. 1 to 5. Fig. 3(a) shows the constellation of the received signal on ch. 3 when the received optical power was -24 dBm. The signal quality was degraded by the nonlinear effect of SPM, XPM and FWM. Fig. 3(b) shows the constellation after compensation using the ANN. The symbol rotation caused by SPM and XPM were compensated for. However, the effect of FWM could not be compensated for, because it was under the influence of the random phase-noise of ch. 1, 2, 4, and 5. Next, we employed the five phase-locked carriers. Fig. 3(c) shows the constellation

of the received signal on ch. 3. Fig. 3(d) shows the constellation after compensation using the ANN. The waveform distortion caused by SPM, XPM, and FWM was compensated for successfully. Fig. 3(e) shows the EVM performance with and without the compensation versus the received optical power. When the individual LDs were used, the EVM was improved by less than about 16% using the ANN at a received optical power of -24 dBm, because the effect of FWM could not be compensated for. When the phase-locked multicarrier source was used, the EVM was improved by more than about 19%, compensating for FWM.

Fig. 3. Constellations and EVM characteristics.

5 Conclusion

We proposed and investigated a FWM compensation scheme using ANN-based digital signal processing. Numerical simulation of WDM transmission showed that the ANN could compensate for the nonlinear waveform distortion caused by SPM, XPM, and FWM. However, more practical evaluation by experimental studies will be necessary in the next step. It is also important to evaluate the performance of the ANN compared with the conventional schemes such as DBP and VSTF.