Demodulation of Eigenvalue Modulated Signal Based on Eigenvalue-Domain Neural Network

Ken Mishina[1], Shingo Sato[1], Shohei Yamamoto[1], Yuki Yoshida[2,1], Daisuke Hisano[1], and Akihiro Maruta[1]

[1] *Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan*
[2] *National Institute of Information and Communications Technology (NICT), Koganei, Tokyo 184-8795, Japan*
mishina@comm.eng.osaka-u.ac.jp

Abstract: A demodulation scheme for an eigenvalue modulated signal based on an eigenvalue-domain neural network is demonstrated experimentally. Successful demodulation is demonstrated at 2.5 Gb/s over a transmission distance of up to 3,000 km.

OCIS codes: (060.2330) Fiber Optics Communications, (190.5530) Pulse propagation and temporal solitons.

1. Introduction

Optical eigenvalue communication [1] based on the inverse scattering transform (IST) [2] has been studied as a means of overcoming the nonlinear Shannon limit [3–10]. The IST is recently well-known as nonlinear Fourier Transform (NFT). Although optical waveforms and frequency spectra change during propagation in a nonlinear dispersive fiber, the eigenvalues of the eigenvalue equation associated with the nonlinear Schrödinger equation are invariant. To increase the spectral efficiency, various eigenvalue modulation schemes have been proposed, such as on-off encoding of multi-eigenvalues [4, 5] and phase shift keying modulation of the spectral amplitude for multi-soliton pulses [6].

For eigenvalue demodulation, the received time-domain signal is converted to an eigenvalue pattern using the IST. After that, a hard decision (HD) with a linear threshold on the eigenvalue plane is performed in the conventional method. However, upon optimizing the decision threshold, the problem is that eigenvalue deviation due to noise and fiber loss is not i.i.d. with the circular Gaussian process, particularly in the case of a multi-eigenvalue system [7, 8]. To improve the received power margin, demodulation methods using a time-domain artificial neural network (ANN) have been demonstrated recently [9, 10]. However, although using a time-domain ANN results in a large power margin of 11 dB compared with the conventional IST+HD method [10], the former approach requires training for each transmission distance because the time-domain pulses change during transmission.

In this paper, we propose and experimentally demonstrate a demodulation scheme for an eigenvalue modulated signal based on an eigenvalue-domain ANN. The proposed scheme is a combination of the IST and an ANN to retain the benefits of invariant eigenvalues during transmission without requiring training for each transmission distance. The proposed demodulation outperforms the conventional IST+HD method by a power margin of 3.8 dB at a bit error rate (BER) of 3.8×10^{-3}. For a transmission distance of 3,000 km, we demonstrate successful demodulation of the eigenvalue modulated signal at a bit rate of 2.5 Gb/s with a BER $< 3.8 \times 10^{-3}$, and the trained ANN demodulator is valid for transmission distances from zero to 3,000 km.

2. Eigenvalue Modulation and Neural Network Based Demodulation

In this work, we used eigenvalue modulation with on-off encoding. Figure 1 shows modulation and three different demodulation schemes. This modulation begins with a sequence of N bits being encoded into an eigenvalue pattern, which is the on-off state of the complex eigenvalue ζ_n on the complex eigenvalue plane. Next, the encoded eigenvalue pattern is converted into an input pulse by using IST [5]. The converted pulse corresponds to a symbol carrying N information bits. The optical eigenvalue modulated signal is transmitted over optical fiber transmission line.

At the receiver, the eigenvalue modulated signal is demodulated after coherent detection. In the conventional IST+HD scheme shown in Fig. 1(a), the received pulse is converted into an eigenvalue pattern by using IST. The detected eigenvalue pattern is decoded into an information bit sequence by setting the linear thresholds appropriately on the complex eigenvalue plane. In previous work [10], a time-domain pulse was input to an ANN, and a decoded information bit sequence was output directly as shown in Fig. 1(b). Figure 1(c) shows the proposed demodulation method based on an eigenvalue-domain ANN. In this method, the ANN inputs are the eigenvalue data that are converted from the time-domain pulse using the IST. The real and imaginary parts of each eigenvalue

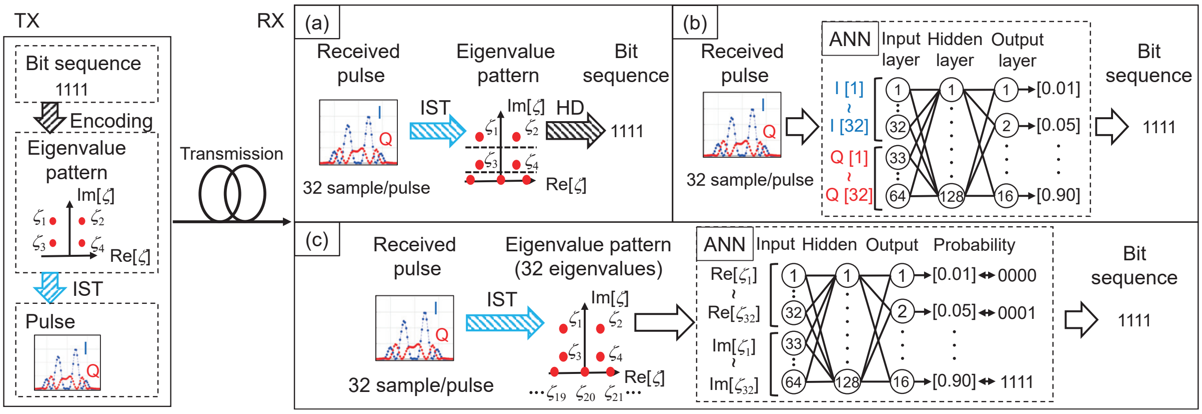

Fig. 1: Modulation and three different demodulation schemes: (a) inverse scattering transform (IST) + hard decision (HD) (conventional method); (b) time-domain artificial neural network (ANN) (previous method), and (c) eigenvalue-domain ANN (proposed method).

are input to the ANN, which outputs the probability parameter of the bit sequence corresponding to the detected eigenvalue pattern. The configuration of the eigenvalue-domain ANN demodulator for four eigenvalues ($N = 4$) is shown in Fig. 1(c). For a sampling rate of 32 samples per pulse, the number of converted eigenvalues including continuous spectrum is also 32, and there are 64 input elements comprising the 32 real and 32 imaginary parts of those eigenvalues. The number of output elements is 16, corresponding to the number of eigenvalue patterns (i.e., $2^4 = 16$).

3. Experimental Setup and Results

Figure 2 shows the experimental setup with an off-line ANN-based receiver. For eigenvalue modulation, we used four eigenvalues of $\zeta = \{(-0.5+0.5i)/2, (0.5+0.5i)/2, (-0.5+1.0i)/2, (0.5+1.0i)/2\} \in \mathbb{C}$ as shown in the inset of Fig. 2. For the eigenvalue modulated signal, the random 62,250 pulses were generated off-line. The optical signal was generated using an arbitrary waveform generator (AWG) operated at 10 Gsample/s and an IQ modulator. The pulse duration was 1.6 ns, each pulse contained up-to four discrete eigenvalues, and the effective bit rate was 2.5 Gb/s. The optical signal was launched into a transmission loop that included a 50-km non-zero dispersion shifted fiber (NZ-DSF) and an erbium-doped fiber amplifier (EDFA). The NZ-DSF parameters were a dispersion parameter of D=4.4 ps/nm/km, a dispersion slope of S=0.046 ps/nm^2/km, a nonlinear coefficient of γ=2.1 W^{-1}/km, and a fiber loss of 0.2 dB/km. The input power was set to –3.0 dBm, which was the calculated ideal average power for the eigenvalue modulation. At the receiver, the received signals were analog-digital converted by a digital storage oscilloscope operated at 40 Gsample/s, and the digital signal was downsampled to 20 Gsample/s. The digital signal processing (DSP) for the demodulation was performed in an off-line manner.

The ANN configuration and parameters for the demodulation were described in Section 2. We used a three-layer perceptron configuration and the rectified linear unit (ReLU) activation function . The number of hidden units was set to 128. We used the soft max function as the output function and the cross-entropy error function as the loss function. The 62,250 received pulses were divided into one sequence of 10,000 pulses for the training and another of 52,250 pulses for BER testing. The ANN was trained using an Adam optimizer [11] from the TensorFlow open-source library. The training data were extracted uniformly from the data sets at an optical signal-to-noise ratio (OSNR) between -2 and 17 dB.

Figure 3 shows the BER curves obtained in the loop-transmission experiments with different demodulation methods and training conditions. Figure 3(a) shows the BER curves for back-to-back (B-to-B). The eigenvalue-domain ANN demodulator outperforms the conventional IST+HD method by a power margin of 3.8 dB at a BER of 3.8×10^{-3} assuming the HD forward error correction (FEC). This is better than with the conventional

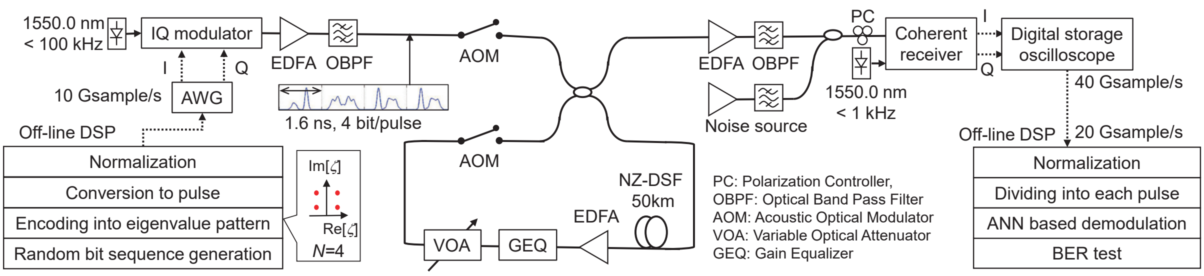

Fig. 2: Experimental setup.

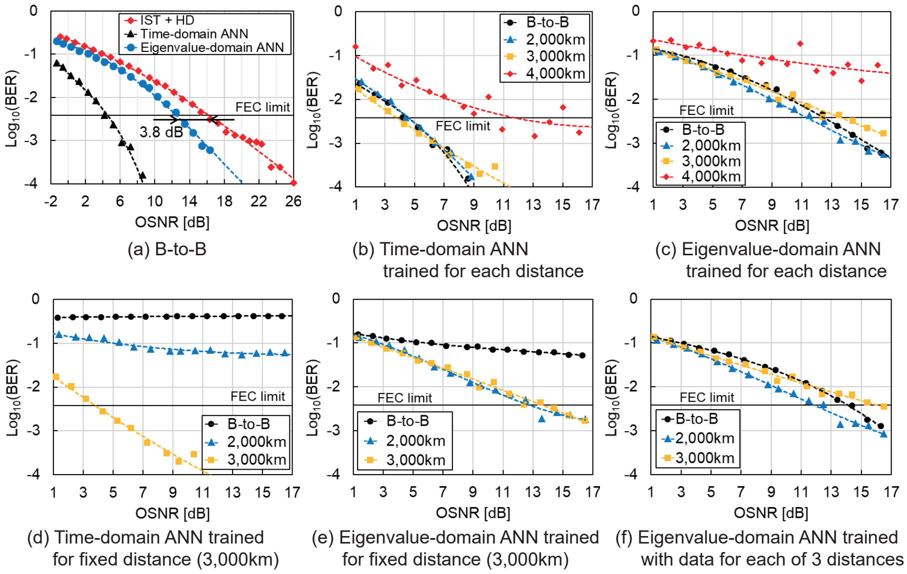

Fig. 3: BER curves in loop-transmission experiments.

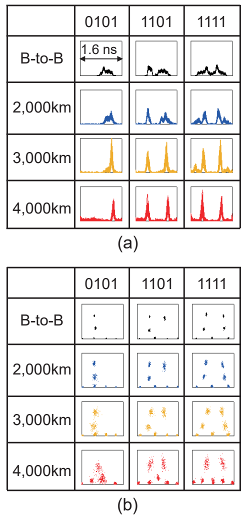

Fig. 4: (a) Waveforms and (b) eigenvalue patterns.

IST+HD method because the Euclidean distance in the 64-dimensional space of the 64-input ANN is larger than that in the two-dimensional space of the complex eigenvalue plane in the IST+HD method. The time-domain ANN demodulator achieves a much better BER in B-to-B because the effect of noise in the discrete eigenvalue-domain is greater than that in the time-domain. Figure 3(b) and (c) show the BER curves before and after transmission when using the time- and eigenvalue-domain ANN demodulators trained for each different transmission distance. Figure 4 shows the received waveforms and detected eigenvalue patterns for representative patterns. After the 4,000-km transmission, there was a large power penalty due to inter symbol interference [10]. The eigenvalue patterns were conserved at 3,000 km, however, the variations in eigenvalue position were greater than those in the B-to B and 2,000-km transmission because of the transmission distortion including fiber loss and amplified spontaneous emission (ASE) noise. This is why the BER curve indicates the error floor under high OSNR at 3,000 km.

Figure 3(d) and (e) show the BER curves when using the time- and eigenvalue-domain ANN demodulators trained for the fixed distance of 3,000 km. In the case of the time-domain ANN, as shown in Fig. 3(d), it is difficult to demodulate the received signal for the different transmission distances because the time-domain pulse shape changes during the fiber transmission. By contrast, as shown in Figure 3(e), the eigenvalue-domain ANN can deal with the received signal for both the 2,000-km and 3,000-km transmissions. These results indicate that the eigenvalue-domain ANN demodulator is superior to the time-domain ANN demodulator in generalization performance of transmission distance owing to the invariance of the eigenvalues. Figure 3(f) shows the BER curves obtained using the eigenvalue-domain ANN trained with 10,000 data for each of three distances, namely zero (i.e., B-to-B), 2,000 km, and 3,000 km. A BER under the FEC limit was achieved for each distance from zero to 3,000 km, thereby showing that the eigenvalue-domain ANN demodulator has the potential to cover a large distance range in the point of generalization performance.

4. Conclusion

We proposed the demodulation of an eigenvalue modulated signal using an eigenvalue-domain ANN and demonstrated it experimentally. The eigenvalue-domain ANN demodulator outperformed the conventional IST+HD demodulator by a power margin of 3.8 dB. Furthermore, we confirmed successful demodulation over distances from zero to 3,000 km without training for each distance.

Acknowledgements This work was supported by JSPS KAKENHI Grant Number JP19H02140.

References

1. A. Hasegawa et al., J. Lightw. Technol., **11**, 395–399 (1993).
2. M. J. Ablowitz and H. Segur, *Solitons and the Inverse Scattering Transform* (SIAM, 1981).
3. S. K. Turitsyn et al., Optica, **4**, 307–322 (2017).
4. S. Hari et al., J. Lightw. Technol., **34**, 3110–3117 (2016).
5. T. Kodama et al., in Proc. PSC2018, Paper Th3C.4 (2018).
6. V. Aref et al., in Proc. ECOC2016, Paper Tu.3.E.1 (2016).
7. J. Garcia et al., in Proc. ECOC2018, Paper We2.18 (2018).
8. Q. W. Zhang et al., Sci. Rep., **9** , 1–17 (2019).
9. R. T. Jones et al., Photon. Technol. Lett., **30**, 1079–1082 (2018).
10. K. Mishina et al., in Proc. ECOC2019, Paper W.1.B.4 (2019).
11. D. Kingma and J. Ba, in Proc. ICLR2015, pp. 1–15 (2015).