Demodulation of optical eigenvalue modulated signal using neural network

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Abstract:
Eigenvalue communication is a promising technology for overcoming capacity limitation due to Kerr nonlinearity in optical fiber. In this letter, we propose an artificial neural network based demodulation method for optical eigenvalue modulated signal using on-off encoding. The proposed method has 9.2 dB power margin at BER = $3.8 \times 10^{-3}$ compared with the conventional inverse scattering transform based demodulation method.

Keywords: Optical fiber communication, machine learning, multi-soliton transmission, optical eigenvalue modulation, neural network

Classification: Fiber-optic transmission for communications

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1 Introduction

Optical eigenvalue communication [1] based on inverse scattering transform (IST) [2] has been studied for overcoming the nonlinear Shannon limit [3]. Eigenvalues of the eigenvalue equation associated with nonlinear Schrödinger equation (NLSE) are invariant during propagation in nonlinear dispersive fiber even though optical waveform and frequency spectra have changed. In 1993, A. Hasegawa and T. Nyu proposed a modulation scheme using eigenvalue for the first time [1]. Owing to recent remarkable development of digital coherent technologies, it became possible to realize the concept of the eigenvalue communication. In order to increase spectral efficiency, various eigenvalue modulation schemes have been proposed, such as on-off encoding of multi-eigenvalues [4, 5] and multi-level PSK in spectral amplitude [6]. In eigenvalue demodulation, the received time-domain signal is converted to eigenvalue pattern by using IST. Eigenvalue detection algorithm based on IST still remains matters to be discussed. The remaining problem is that eigenvalue distortion arising from noise and actual transmission is not i.i.d. with Gaussian process especially in the case of multi-eigenvalue system [7, 8]. For improvement of received power margin, another decision process based on the Euclidian minimum distance has been demonstrated [9]. Furthermore, a machine learning based demodulation method using artificial neural network (ANN) for QPSK modulation of spectral amplitude in two eigenvalues has been recently proposed [10, 11]. However, there has been no study on ANN based demodulation scheme for eigenvalue on-off encoded signal with more than two eigenvalues.

In this letter, we propose a demodulation method using ANN for eigenvalue modulated signal based on on-off encoding of four eigenvalues. The proposed method has 9.2 dB power margin improvement at the bit error rate (BER) of $3.8 \times 10^{-3}$ compared with the conventional demodulation based on IST. We demonstrate successful demodulation of four eigenvalue modulated signal after 1,000 km.
transmission. Moreover, we report the demodulation performance dependency on hyperparameters of neural network: numbers of input elements and hidden units.

2 Demodulation method and simulation model

Eigenvalue equation associated to normalized NLSE is described as

\[ i \frac{\partial \psi_1}{\partial T} + u \psi_2 = \zeta \psi_1, \quad -i \frac{\partial \psi_2}{\partial T} + u^* \psi_1 = \zeta^* \psi_2, \tag{1} \]

where \( \zeta, \psi_l(T, Z) (l = 1, 2) \) are complex eigenvalue and eigen functions [1]. As far as complex envelope amplitude \( u(T, Z) \) satisfies NLSE, eigenvalue is invariant with respect to transmission distance \( Z \).

Figure 1 shows concept of the eigenvalue modulation/demodulation method and simulation model. In the eigenvalue modulation using on-off encoding of \( N \)-eigenvalues, \( N \) bit sequence is encoded to an eigenvalue pattern, which is the on-off state of the complex eigenvalue \( \zeta_n \) on the complex eigenvalue plane. Then, the encoded eigenvalue pattern is converted to input pulse using IST [5]. The optical eigenvalue modulated signal is generated by I-Q modulator, and then transmitted over optical fiber transmission line.

At the receiver, eigenvalue modulated signal is demodulated after coherent detection. A conventional demodulation method based on IST is shown in Fig. 1 (a). The received digital I/Q signal is normalized by using fiber and pulse parameters, and the normalized signal is divided into each pulse. The divided pulse is converted to the eigenvalue pattern using IST. In this work, we employed Fourier collocation method for eigenvalue detection, which is performed by
solving the eigenvalue problem of the matrix equation (1) in the frequency domain [12]. The detected eigenvalue pattern is decoded to the information bit sequence through decision.

The proposed demodulation method based on ANN is shown in Fig. 1 (b). In this method, the time series data of the received pulse are input to ANN, and the decoded information bit sequence is directly output. Specifically, the I/Q components of each sample point of the pulse shape are used as input elements of the ANN, and the probability factor of the bit sequence corresponding to the detected eigenvalue pattern is taken as output elements of the ANN. The configuration of the ANN based demodulator for four eigenvalues ($N=4$) is shown in Fig. 1 (b). In the case of sampling rate of 32 sample/pulse, the number of the input elements is 64 that consists of 32 I/Q components. The number of output elements is 16 that corresponds to the number of on-off eigenvalue patterns of $2^4$.

We investigated the performance of the proposed ANN based demodulation method by numerical simulations. In this simulation, we employed four arbitrary positioned optical eigenvalues of $\zeta=\{(-0.5+i0.5)/2, (0.5+i0.5)/2, (-0.5+i1.0)/2, (0.5+i1.0)/2\}\in\mathbb{C}$ on the complex eigenvalue plane. For the eigenvalue modulated signal, the random 35,000 pulses were generated. The modulation was performed at 10 Gsample/s (16 sample/pulse). The pulse duration was 1.6 ns, and the bit rate was 2.5 Gb/s. The non-zero dispersion shifted fiber (NZ-DSF) transmission link was divided into 50 km erbium doped fiber amplifier (EDFA) spans. The parameters of NZ-DSF were dispersion parameter $D=17$ ps/nm/km, nonlinear coefficient $\gamma=1.2$ W/km, and fiber loss 0.2 dB/km. For the simulation, we adopted a three-layer perceptron configuration and activation function of rectified linear unit (ReLU). We used soft max function as output function and cross-entropy error function as loss function. For standard condition, we used the following parameters: the sampling rate of 32 sample/pulse, the number of the input elements of 64, and the number of the hidden units of 128. The received random 35,000 pulses were divided into two pulse sequences of 10,000 and 25,000 pulses for the training and BER test, respectively. The ANN was trained using an Adam optimizer of TensorFlow. The training was performed using the received pulses under an $E_b/N_0$ condition around BER= $10^{-4}$.

### 3 Simulation results

Figure 2 (a) shows the BER curves for the back-to-back condition. Compared with the conventional IST based demodulation, the ANN based demodulation scheme achieved $9.2$ dB power margin improvement at BER of $3.8 \times 10^{-3}$ assuming the hard decision forward error correction (FEC). This is because that the standardized Euclidean distance in 64-dimensional space of the time-domain 64 inputs ANN is longer than that in 2-dimensional space of complex eigenvalue plane after IST. The ANN based demodulation results after the NZ-DSF transmission are shown in Fig. 2 (b). The power penalty increases with increase in the transmission distance when using the ANN trained at B-to-B. This is because that time-domain pulse shape changes during transmission even though eigenvalue pattern is invariant. On the other hand, when the training is performed
Fig.2 (a) BER curves of the back-to-back with the conventional and proposed demodulation schemes, and (b) BER curves using ANN based demodulation before and after the NZ-DSF transmission.

Fig.3 $E_b/N_0$ at BER = $3.8 \times 10^{-3}$ with changing the hyperparameters.

by each transmission distance, almost no power penalty can be observed even after the 1,000 km NZ-DSF transmission. The generalization ability of the proposed ANN demodulator against transmission distance variation is open to discussion.

Furthermore, we investigated demodulation performance dependency on hyperparameters of neural network: numbers of input elements and hidden units. Figure 3 shows $E_b/N_0$ at BER = $3.8 \times 10^{-3}$ for B-to-B with changing the hyperparameters. As shown in Fig. 3, 8 input units are sufficient, and no improvement is observed with 16 or more input elements in the case of B-to-B. This result indicates that sampling rate of 8 sample/pulse can cover almost spectral information of the eigenvalue modulated signal. The number of hidden units should be more than twice the number of input elements, namely fourfold the number of sampling point/pulse. Note that required sampling rate depends on parameters of eigenvalue modulation and extra hidden units increase risk of overfitting to training pattern and noise.

4 Conclusions
We proposed an ANN based demodulation method for optical eigenvalue modulated signal using on-off encoding of arbitrary positioned optical multi-
eigenvalue. The proposed method showed 9.2 dB power margin improvement compared with the conventional IST based demodulation. We demonstrated successful demodulation of four eigenvalue modulated signal after the 1,000 km transmission. Furthermore, we reported the required number of input and hidden layers for the proposed eigenvalue demodulation.

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