

Eigenvalue-domain Neural Network Receiver for 4096-ary Eigenvalue-modulated Signal

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Abstract: Demodulation scheme based on multilabel eigenvalue-domain neural network for a 4096-ary eigenvalue-modulated signal is demonstrated experimentally. Successful demodulation with a 2.5 dB power margin compared with multiclass single-label classification is achieved at 10.7 Gb/s.

1. Introduction

Eigenvalue communication [1] based on inverse scattering transform (IST) is a promising approach to overcome the Kerr nonlinear limit [2–6]. IST is recently well-known as a nonlinear Fourier transform (NFT). To increase transmission capacity, many studies have been conducted on multilevel and multieigenvalue modulations, such as 64-QAM of the nonlinear spectrum [2] and on–off encoding of multieigenvalue [3]. As high-order multilevel modulation, we demonstrated a transmission of a 4096 ($= 2^{12}$)-ary eigenvalue modulated signal [4].

Recently, machine learning-based approaches for IST-based communication systems have been studied to improve the receiver sensitivity [5]. For the on–off encoding, an eigenvalue-domain (ED) neural network (NN)-based receiver was proposed [6]. The ED-NN receiver has the advantage of no model retraining for each transmission distance because the eigenvalue is invariant during lossless fiber propagation. However, an ED-NN receiver for high multilevel modulation, such as 2^{12}-ary modulation, is yet to be studied.

In this study, we experimentally and numerically investigate the applicability of the ED-NN receivers to the demodulation of the 2^{12}-ary eigenvalue-modulated signal at 10.7 Gb/s. The ED-NN receiver using a multiclass single-label (MCSL) classification in [6] does not work well with several thousands of training samples because the ED-NN has a lot of output units. Therefore, we propose applying multilabel classification and binary relevance (BR) methods [7] to ED-NN receivers to improve the demodulation performance. In the transmission experiment, the multilabel and BR ED-NN receivers demonstrate the better bit error rate (BER) characteristics with power margins of 2.5 and 2.9 dB compared with the MCSL ED-NN receiver, respectively. In addition, the multilabel ED-NN provides well-balanced performance in both BER and circuit complexity. In the simulation, the multilabel ED-NN receiver is valid for different transmission distances up to 200 km without retraining.

2. Eigenvalue Modulation and ED-NN-based Receiver

Fig. 1 illustrates 2^{12}-ary eigenvalue modulation based on the on–off encoding [4] and ED-NN-based demodulation. In this method, a bit sequence of 12 bits is encoded into an eigenvalue pattern corresponding to an on–off state of 12 eigenvalues. The eigenvalue pattern is converted into a higher-order soliton pulse following a one-to-one mapping rule [3]. The numbers of eigenvalue and pulse patterns are 2^{12}. A coherent receiver obtains a complex envelope amplitude of the received soliton pulse. An eigenvalue pattern is detected from the soliton pulse by IST. Consequently, the detected eigenvalue pattern is decoded into a bit sequence of 12 bits. The most significant feature of the eigenvalue modulation is that the eigenvalue pattern is invariant during the lossless fiber transmission, although the pulse shape and spectrum change by dispersion and Kerr nonlinearity.

We employed the ED-NN classification for decoding from the eigenvalue to the bit sequence. Fig. 1(a) shows an ED-NN receiver based on MCSL classification as the conventional method [6]. The input of the ED-NN was all detected eigenvalues. The number of detected eigenvalues is N_s when the sampling rate is N_s samples per pulse at the receiver. N_s was set to 64 in this study. The eigenvalue patterns were classified into 2^{12} classes corresponding to the bit sequence with a softmax function.

In this study, we propose applying multilabel and BR methods [7] to ED-NN receivers, shown in Fig. 1(b) and (c), respectively. In the multilabel classification method, although the input and hidden layers were the same as in the MCSL ED-NN, only the output layer differed. The number of output units was 12 corresponding to the number of the eigenvalues (bits) for encoding. A logistic sigmoid function was used for the output function. The input data were linked with the multilabel, namely the multi-on-state of the eigenvalues when more than one

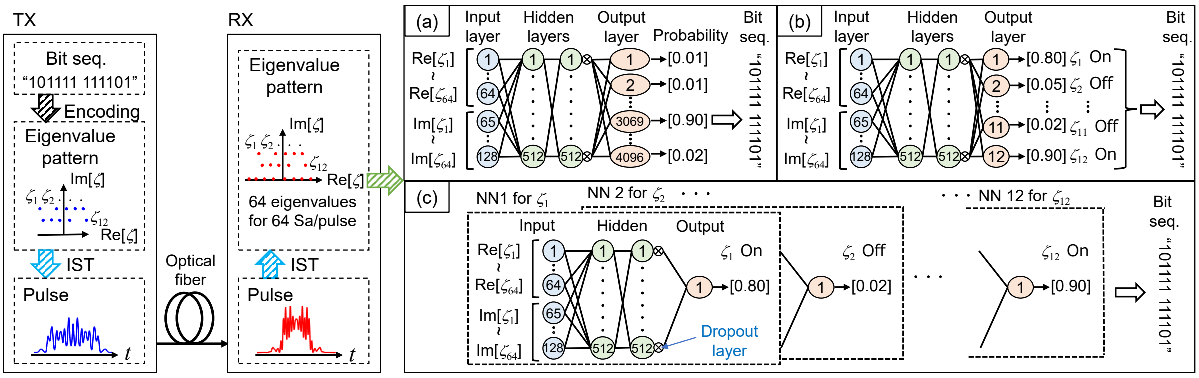

Fig. 1: 2^{12}-ary eigenvalue modulation and ED-NN demodulation; (a) MCSL, (b) multilabel, and (c) BR.

output exceeded the threshold. In the BR method, we prepared 12 NN receivers to classify the on–off states of 12 eigenvalues, respectively. Each ED-NN had the same input layer as the MCSL ED-NN and one output unit with a logistic sigmoid function, which identified an on-off state of each eigenvalue. Both proposed ED-NNs could be optimized with smaller training symbols than in the MCSL ED-NN because the number of output units was smaller than in the MCSL method. We adopted a four-layer perceptron configuration with two hidden layers for the three ED-NN receivers. The rectified linear unit activation function was used in hidden units.

3. Experiments

Fig. 2 shows the experimental setup and parameters to investigate the applicability of the proposed ED-NN receivers to the 2^{12}-ary eigenvalue-modulated signal. We employed the on–off encoding of the triangular-lattice-shaped 12 eigenvalues as in [4]. The pulse duration was set to 1.07 ns, and the bit rate without a 7% overhead of the forward error correction (FEC) was 10.7 Gb/s. The optical eigenvalue-modulated signal was launched into 50-km non-zero dispersion-shifted fiber (NZ-DSF), which had the parameters shown in Fig. 2. The propagated signal was amplified using a Raman pump and an erbium-doped fiber amplifier (EDFA).

At the receiver, the signal was demodulated using the ED-NN receivers offline at 60 GSa/s, which corresponded to $N_s = 64$ samples per pulse. The numbers of input, the first hidden units, and second hidden units were 128, 512, and 512 for all three ED-NNs, respectively. We inserted a dropout layer with a probability of 0.6 after the second hidden layer during training. The ED-NNs were trained using the Adam optimizer with the early stopping algorithm. Different pulse sequences were used for the training and BER test.

Fig. 3(a) shows the detected eigenvalue patterns of all 2^{12} pulses before and after the 50-km transmission under the best optical signal-to-noise (OSNR) conditions. The eigenvalue patterns were conserved during the transmission. Figs. 3(b) and (c) show the BER curves using the three ED-NN receivers trained with 2^{12} and $2^{12} \times 8$ training pulses, respectively. Notably, "$2^{12} \times 8$" means that eight measured data of the same pulse sequence on the digital storage oscilloscope were used for training. When the number of training symbols was 2^{12}, the MCSL ED-NN could not achieve a BER below the FEC limit of BER$= 3.8 \times 10^{-3}$. Meanwhile, both multilabel and BR methods attained error-free operations with the FEC. Although the BER performances were improved by increasing the number of training symbols to $2^{12} \times 8$, the multilabel and BR ED-NN receivers demonstrated the improved BER with power margins of 2.5 and 2.9 dB compared with the MCSL method, respectively. Fig. 3(d) shows a number of weights of the three ED-NNs to compare the circuit complexities. The BR ED-NN receiver required a larger circuit size because it consisted of 12 NNs. On the other hand, the multilabel ED-NN provided well-balanced performance in BER and circuit complexity because the number of weights was smaller than those of the other two methods by one order of magnitude.

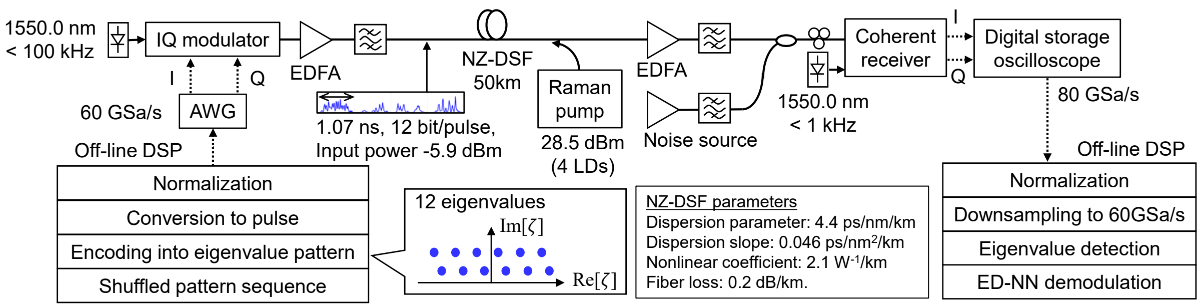

Fig. 2: Experimental setup.

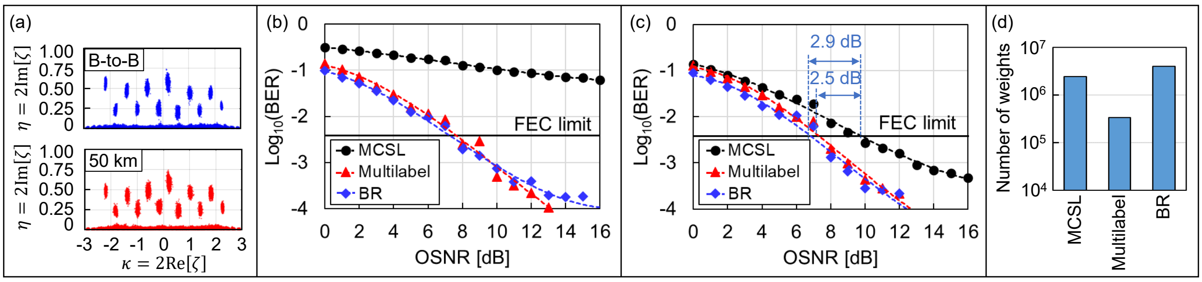

Fig. 3: Experimental results: (a) Eigenvalue patterns. BER curves after the 50-km transmission using the ED-NNs trained with (b) 2^{12} and (c) $2^{12} \times 8$ training pulses. (d) Number of weights.

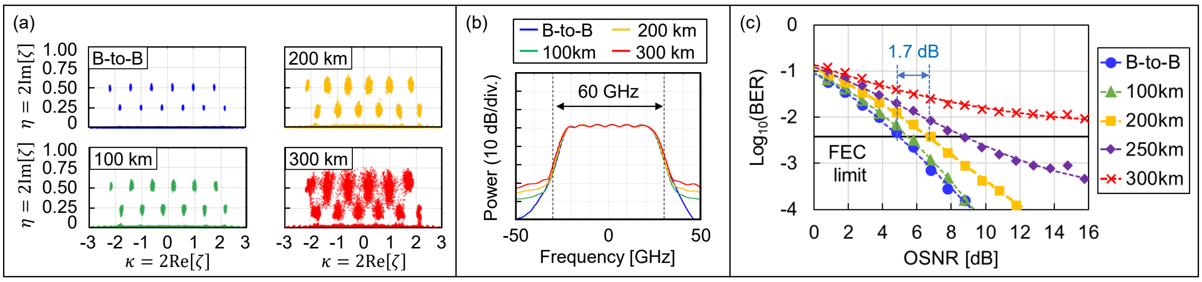

Fig. 4: Simulation results: (a) Eigenvalue patterns, (b) spectra, and (c) BER curves.

4. Simulations for Long-haul Transmission

To complement the investigation of the applicability to long-haul transmission, we performed a transmission simulation based on the split-step Fourier method. The simulation parameters for modulation and demodulation were the same as the experimental parameters. In the simulation, we constructed a transmission loop comprising an NZ-DSF and Raman pump, which had the same parameters as in the experiments. Fig. 4(a) shows the eigenvalue patterns before and after transmission. The eigenvalue pattern significantly changed due to the fiber loss and the limitation of the sampling rate when the transmission distance was 300 km. Because the spectrum broadened during the transmission as shown in Fig. 4(b), a higher sampling rate was required to suppress the eigenvalue change. Although we used the same NZ-DSF parameters as in the experiments, the fiber loss and spectral broadening effects can be mitigated by using smaller dispersion parameter to elongate the dispersion length.

Fig. 4(c) shows the BER results of the transmission simulation when using the multilabel ED-NN receiver. The ED-NN was trained using mixed training symbols of the different transmission distances of 0, 100, and 200 km ($2^{12} \times 3$). The multilabel ED-NN receiver could be valid for the long-haul transmission over 200 km without a large OSNR penalty > 2 dB and retraining for each transmission distance.

5. Conclusions

We proposed multilabel and BR ED-NN receivers for 4096-ary eigenvalue-modulated signal. The proposed receivers demonstrated improved BER performance compared with the MCSL method in an experiment. A simulation demonstrated the validation of the multilabel ED-NN receiver over a transmission distance of 200 km.

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