800-Gbps PAM-4 2-km Transmission using 4-λ LAN-WDM TOSA with MLSE based on Deep Neural Network

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Abstract: We propose an MLSE based on a deep neural network that estimates nonlinear channel responses. We demonstrate 224-Gbps/λ 2-km transmission using 4-λ LAN-WDM TOSA and the proposed method with a BER below the HD-FEC limit. © 2022 The Authors

1. Introduction

With the rapid spread of cloud and social media services over the last few years, traffic on data center networks (DCNs) has continued to increase. In DCNs, traffic is concentrated on connections within and between DCs. The very large number of connection ports has been supported by Ethernet, which can be economically deployed. Ethernet has been standardized up to 400GbE with 100-Gbps per channel using the O-band and the intensity modulation direct detection (IM-DD) system. To meet the increasing demand for 400GbE, 800GbE, and beyond, 800GbE and 1.6TbE standards have been set as objectives [1]. These standards are also expected to include 200-Gbps per channel and will be applied to further economize on 200GbE and 400GbE. However, the optical transmission of 200-Gbps per channel will require very high speed modulation, and there are several challenges to its economic realization. The main problem is the significant degradation in signal quality due to inter-symbol interference (ISI) caused by bandwidth limitations and chromatic dispersion (CD). Furthermore, due to the nonlinear response caused by device response and the interaction between CD and direct detection, conventional linear equalization methods are no longer able to address severe nonlinear ISI. Therefore, several studies have been conducted to solve the serious signal distortion caused by large nonlinear ISI with high-baud-rate signal transmission with an equalizer using a Volterra filter or a neural network (NN) [2-5]. We previously investigated an advanced MLSE that is able to estimate a transfer function that is nonlinearly distorted by nonlinear ISI. This technique can calculate metrics without noise enhancement from nonlinear calculation and high-frequency-component equalization [6, 7]. A similar approach to improving MLSE is research on the application of memoryless NN with a hidden layer as a transfer function estimator for satellite communication systems [8]. In this paper, we propose MLSE using a deep neural network (DNN) as the transfer function estimator (DNN-MLSE) to improve the performance of short-reach optical transmission systems with a nonlinear channel response. We also demonstrate 800-Gbps PAM-4 2-km transmission using 4-ch LAN-WDM TOSA and DNN-MLSE. In addition, we discuss the performance of DNN-MLSE by comparing the transmission performance of different scales of DNN configurations.

2. MLSE based on deep neural network

Figure 1 shows a block diagram of the proposed DNN-MLSE. This method consists of two adaptive filters, a multi-layer perceptron, a Viterbi decoder, and a candidate sequence generator. The first filter is a channel shortening filter (CSF) that fixes the sampling phase of the received signal and shortens the overall impulse response length of received signal sequences to suppress the increase in the calculation amount in accordance with the memory length of the Viterbi decoder. The second filter is an adaptive low pass filter (A-LPF) that suppresses high-frequency noise components that were increased by the CSF in the previous stage. The multi-layer perceptron is adopted as a desired impulse response (DIR) estimator that converges with the same distance function as the A-LPF so that it can simulate the frequency response of the transmission system, i.e., the frequency response that is least affected by Gaussian noise.

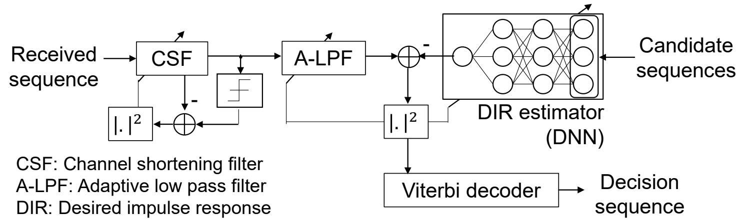

Fig. 1. Block diagram of DNN-MLSE.

The multi-layer perceptron for reproducing the transfer function is an iteration of an asymptotic equation. The asymptotic equation of the i-th layer is expressed as

$$X_{i+1} = f(A_i X_i + B_i) \tag{1},$$

where X_{i+1} is the i-th layer output vector, f is the nonlinear function, X_i is the i-th layer input vector, A_i is the i-th weight parameter matrix, and B_i is the i-th bias parameter and can represent an iteration of linear convolution and nonlinear function f in the transfer function. We use the hyperbolic tangent function or Rectified Linear Unit (ReLU) as the nonlinear function in the multi-layer perceptron. The first layer is the input layer, and the number of nodes in this layer represents the number of memories in the Viterbi algorithm. The last layer is the output layer, the number of nodes in this layer is used to calculate the metrics for the Viterbi algorithm and is set to one. The complexity of the transfer function of the multi-layer perceptron can be adjusted by changing the number of hidden layers and the number of nodes in each hidden layer, and adjusting the complexity is effective in improving the accuracy of the transfer function estimation. The pre-training of the multi-layer perceptron is done by using the training sequence as the input of the multi-layer perceptron and the transmission signal and by using the back propagation method to minimize the squared error between the output of the multi-layer perceptron and the received signal processed by CSF and A-LPF. Then, the weights of the multi-layer perceptron can be updated adaptively by using the decision results as the input of the multi-layer perceptron even in normal operation.

3. Experimental setup and Results

We experimentally evaluated the performance of the proposed DNN-MLSE in 800-Gbps PAM-4 2-km transmission. Figure 2 shows the experimental setup. Transmission data sequences of 224-Gbps PAM-4 signals were generated by off-line DSP and a 65-GHz, 112-Gsample/s arbitrary waveform generator (AWG). In this experiment, a 15th-order pseudo-random binary sequence was utilized. The electrical PAM-4 signals were modulated to 4-ch WDM optical signals by a 4-λ LAN-WDM TOSA that consisted of electro absorption modulated lasers (EMLs) with integrated semiconductor optical amplifiers (SOAs) and a wavelength multiplexer [9]. The optical signals were transmitted to 2-km SMF without any optical amplifiers. The transmitted optical signals were received with a 50-GHz PIN photodiode (PD) after implementing a wavelength de-multiplexer (LAN-WDM DeMUX) and a variable optical attenuator (VOA). The amount of chromatic dispersion was −4.2 ps/nm in the case of 2-km transmission at 1295 nm. The received signals were then converted into a digital signal sequence by a 65-GHz, 160-Gsample/s digital storage oscilloscope (DSO) and demodulated by the feed forward equalizer (FFE) and the DNN-MLSE. The FIR filter in the FFE and the CSF in the DNN-MLSE had 45 T/2-spaced taps. The number of taps for the A-LPF and the number of nodes in the input layer in the multi-layer perceptron used as the DIR estimator were set to five. The multi-layer perceptron had 0 to 5 hidden layers, and each hidden layer had 10 to 150 nodes. The FIR filter, the CSF, and the A-LPF were updated by the recursive least squares algorithm. Figure 3 shows the frequency responses of the transmission system, where we can see that the 10-dB frequency bandwidth was 34.8 GHz. Figure 4 (a) shows the results of 112-GBd PAM-4 in 2-km transmission for all lanes where the received optical power was 2 dBm with demodulation by FFE (triangle) and DNN-MLSE. The DNN configuration of the multi-layer perceptron was set to without hidden layers (circle), one hidden layer (diamond) , two hidden layers (square) , three hidden layers (asterisk) and four hidden layers (cross) and the number of nodes in each hidden layer was set to 50. This result show that demodulation by FFE and DNN-MLSE without and with one hidden layer cannot achieve a BER below 3.8×10^{-3} in all or some channels, which corresponds to a 7% overhead HD-FEC limit. In comparison, in the cases of using DNN-MLSE with more than two hidden layers, they were below the HD-FEC limit in all wavelength channels. Figure 4 (b) shows the relationships between the received optical power and BER at lane 1 (1300 nm). In the limit of HD-FEC, these performances were almost the same. This means that even if the number of hidden layers is two, the transfer function was still well estimated in this case. Figure 5 shows a comparison of the performances of the DNN-MLSE for different numbers of hidden layers in

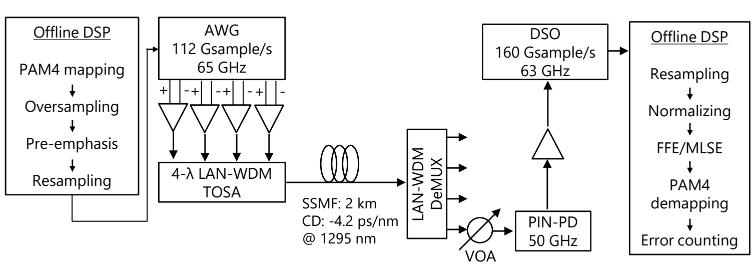

Fig. 2. Experimental setup of 4-ch LAN-WDM transmission.

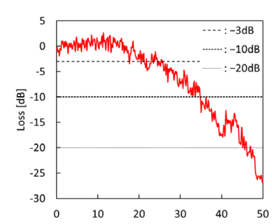

Fig. 3. Frequency responses of transmission system.

all lanes where the received optical power was 2 dBm. The transmission performance tended to improve as the number of hidden layers was increased. However, when the number of hidden layers exceeded a certain number, the multi-layer perceptron did not train well, and the transmission performance deteriorated. Figure 6 shows a comparison of the performances of the DNN-MLSE for different numbers of nodes in the hidden layers in all lanes where the received optical power was 2 dBm. It can be seen that increasing the number of nodes as well as the number of hidden layers tended to improve the transmission performance. In particular, the effect of the performance improvement was strong when the number of nodes was between 10 and 50, and the effect was less when the number of nodes was more than 50.

4. Conclusion

We proposed DNN-MLSE to improve transmission performance through the high-accuracy estimation of a multi-layer perceptron. Experimental results showed it could achieve a BER below the 7% HD-FEC threshold for 800-Gbps 2-km transmission using 4-λ LAN-WDM TOSA. We also compared performances with the different number of hidden layers and nodes in DNN-MLSE.

Acknowledgement: We would like to thank Furukawa Electric Co., Ltd. for contributing the 4-λ LAN-WDM TOSA.

5. References

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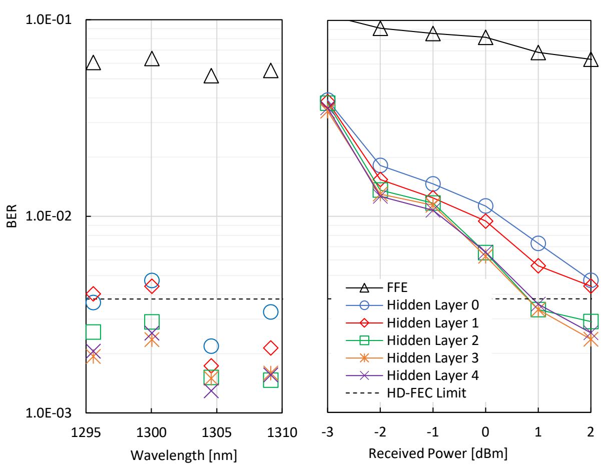

(a) (b)

Fig. 4. 224-Gbps 2-km transmission performance at all lane (a) and lane 1 (b) (FFE and DNN-MLSE with 0 to 4 hidden layers).

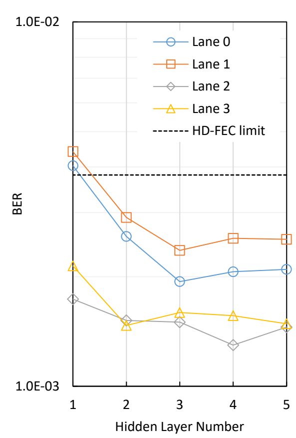

Fig. 5. Comparison of each channel performance for 800-Gbps 2-km transmission with different numbers of hidden layers in DNN-MLSE.

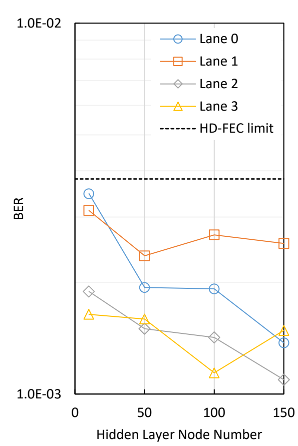

Fig. 6. Comparison of each channel performance for 800-Gbps 2-km transmission with different numbers of nodes in DNN-MLSE.