Neural Network Based Electrical Dispersion Pre-Compensation for Intensity-modulation and Direct-detection Systems

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***Abstract*—Based on deep neural network (DNN), intensity modulation and direct detection (IM/DD) system is demonstrated by simulation and 56-GBaud OOK signal is successfully transmitted over 80-km single mode fiber (SMF) with 3-taps post-equalization.**

Keywords—IM/DD, chromatic dispersion pre-compensation, direct detection, neural network

I. INTRODUCTION

In recent years, a variety of innovative high bandwidth services have increasingly emerged to meet people's requirements for information interaction which has driven the growing number of network users and end devices. To address the dramatic increase in data traffic demand in data centers and metro network applications, the intensity modulation and direct detection (IM/DD) system with simple structure has always been the mainstream solution, relying on its own cost and power consumption advantages [1]. There are various advanced modulation formats already in use in current IM/DD systems, of which on-off keying (OOK) and 4-level pulse amplitude modulation (PAM4) are still the most popular as a result of their easy implement. Nevertheless, the transmission performance is severely restricted due to power fading, which is induced by the interaction between square-law detection and chromatic dispersion (CD) in C-band. Since phase information is not available in IM/DD structure, many existing electrical dispersion compensation techniques cannot be directly applied to compensate for dispersion. As a result, CD is the primary impediment to the IM/DD system realizing high-capacity long-distance transmission [2]. To address this critical problem, multiple methods have been proposed in particular different digital signal processing (DSP) techniques. Unlike complex signal modulation such as vestigial-sideband modulation [3], single-sideband modulation coupled with a KK receiver [4] and two-dimensional modulation [5], DSP techniques eliminate the need to modify the IM/DD architecture, which leads to the system cost increase. DSP approaches include traditional decision feedback equalizer (DFE) [6], Volterra based nonlinear equalizers (VNLE) [7], maximum likelihood sequence estimation (MLSE) [8]. In addition, nonlinear equalization based on neural networks (NN) has recently been employed in optical transmission, inspired by the advancement in machine learning [9-11].

Recently, by measuring intensity only, an iterative algorithm known as Gerchberg-Saxton (GS) algorithm, which has been used in a wide range of applications for phase recovery [12], draws enormous interest and concern. This algorithm is applied in electrical dispersion pre-compensation (pre-EDC) for IM/DD system by treating phase information at the receiver and amplitude information at the transmitter as unconstrained. After first being proposed through simulation [13], various extensive methods to accelerate the speed of convergence and lower computation complexity and latency have been widely investigated and demonstrated experimentally such as the introduction of the digital extinction ratio [14], pilot symbols [15, 16], degrees of freedom [17], reversing factors [17, 18]. And yet they all require real-time iterations, making them unrealistic. More recently, it is reported that the non-iterative feed-forward static digital GS-based finite impulse response (GS-FIR) filter is demonstrated experimentally at the transmitter [19, 20] and by numerical simulation in combination with a functional NN link (FNNL) equalizer at the receiver [21]. With the introduction of FNNL, this scheme enables 112 Gb/s OOK transmission over 20-km single mode fiber (SMF) successfully. However, the taps number of the GS-FIR filter is so high as 449 that it is almost impractical to be implemented.

In this letter, we propose a promising pre-EDC scheme based on deep neural network (DNN) equalizer and the scheme is verified in a 56-Gb/s 80-km IM/DD OOK system by simulation. Furthermore, the effects of the parameters of the DNN are also investigated. The simulation results show that the bit error rates (BER) of 56-Gb/s OOK signal over 80-km SMF transmission with 15 iterations of basic GS pre-EDC scheme and our proposed DNN based scheme are 1.3×10^{-3} and 4.2×10^{-4}, respectively, while only a 3-taps feedforward equalizer (FFE) is employed at the receiver side. The results indicate that our proposed scheme is a promising potential solution for 50-Gbps class 80-km metro optical networks based on the IM/DD structure.

II. NEURAL NETWORK PRE-COMPENSATION SCHEMATIC

The neural network employed in our scheme, as shown in Fig. 1, is based on DNN equalizer which consists of an input layer, a certain number of hidden layers and an output layer. In addition, neurons outputs in adjacent layers are numerically dependent because all of the layers are fully interconnected. The DNN acts as a filter to mitigate the CD induced inter symbol interference (ISI). The number of neurons in the input vector $\mathbf{h_0}$ consists of the symbol itself and some of its precursors and posteriors with the memory length of L, as shown in (1), where $x(n)$ is the nth sample of the data sequence to be transmitted. This means that there are $2L + 1$ neurons in the input layer.

$$\mathbf{h}_0 = [x\,(n-L), x\,(n-L+1), \ldots, x\,(n+L)] \tag{1}$$

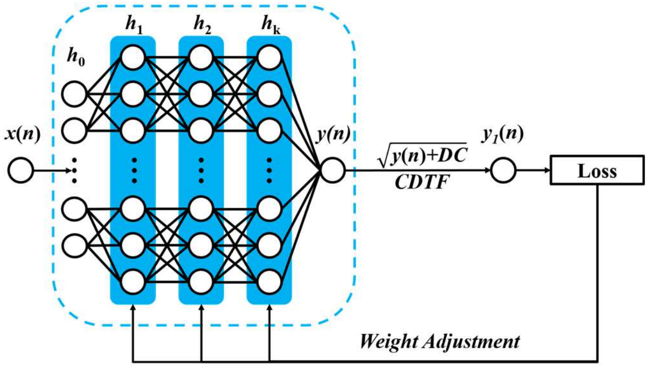

Fig. 1. Structure of the DNN in the pre-EDC scheme.

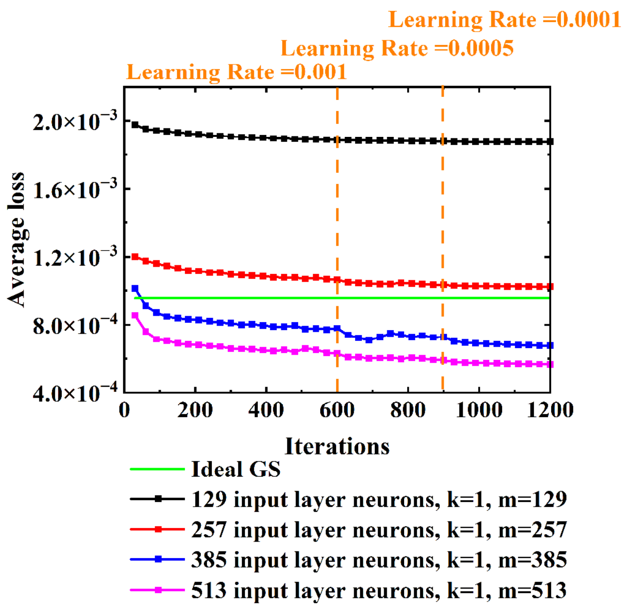

Fig. 2. MSE versus iterations during training of DNN under different input and hidden layer neurons.

There are k hidden layers with m neurons per layer and these super parameters should be optimized during training since they have influence on the complexity and effectiveness of the DNN equalizer. The output of each hidden layer $\mathbf{h}_i$ is the weight matrix $\mathbf{w}_i$ and bias vector $\mathbf{b}_i$ under the activation function of hyperbolic tangent which is introduced to obtain a better fitting non-linear model. We avoid using popular ReLU or sigmoid function as the activation function because they cause DNN to perform worse on our job. The output of each hidden layer can be written as (2).

$$\mathbf{h}_i = f\,(\mathbf{w}_i * \mathbf{h}_{i-1} + \mathbf{b}_i) \tag{2}$$

And the output of the DNN is expressed as (3).

$$\boldsymbol{y}\,(\boldsymbol{n}) = f\,(\mathbf{w}_{k+1} * \mathbf{h}_k + \mathbf{b}_{k+1}) \tag{3}$$

The DNN is designed for nonlinear regression, and the outputs $\boldsymbol{y}\,(\boldsymbol{n})$ will be left as a pre-EDC signal for electro-to-optical conversion. For intensity modulation, the optical intensity is obtained by linearly transforming the electrical amplitude. And the optical intensity can be regarded as the sum of the bipolar signal $\boldsymbol{y}\,(\boldsymbol{n})$ created by DNN and an appropriate DC value. The square root operation on optical intensity is then used to derive the optical amplitude of the pre-compensated signal $\boldsymbol{y}_1\,(\boldsymbol{n})$ and the label signal. Following that, $\boldsymbol{y}_1\,(\boldsymbol{n})$ is transferred from the transmitter side to the receiver side by the chromatic dispersion transfer function (CDTF). The weights between layers are adjusted to minimize the mean square error (MSE) between $\boldsymbol{y}_1\,(\boldsymbol{n})$ and label signal of DNN equalizer during training, and they will be fixed afterwards for testing. By the end of the DNN, the output $\boldsymbol{y}\,(\boldsymbol{n})$ will develop into a one-dimensional real-valued pre- compensated signal with the label amplitude information after transmission over the fiber link in IM-DD systems. Fig. 2 shows the training MSE between the signal for pre- compensation and the labels versus iterations. The learning rate decreases from 0.001 to 0.0005 and 0.0001 when the number of iterations is 600 and 900 respectively to obtain better regression performance. To match the number of neurons in the hidden layer with that in the input layer, the number of both are set to be the same. According to the results, the number of the neurons in input layer have the largest impact on the MSE performance and is set as 513 to mitigate ISI, when the hyper-parameters k is set as 1.

III. Simulation and Results

The verification of the proposed scheme effectiveness is demonstrated on simulation by MATLAB and VPI-transmissionMaker. Fig. 3 gives out the simulation setup and offline DSP in the transceivers, including generation and reception of OOK signal. The 56-GBaud OOK signals are generated offline in MATLAB with a system up-sampling rate of 112-GSa/s, followed by a raised-cosine (RC) filter with a roll-off factor of 1 for Nyquist shaping. Then the signal is GS-based iterated or DNN-based pre-compensated for comparison. The electro-to-optical conversion of the signal is achieved utilizing a chirp-free Mach-Zehnder modulator (MZM) with V_π of 5-V, extinction ratio of 35-dB, and insertion loss of 3-dB. The voltage peak-to-peak (V_{PP}) value of the RF signal is restricted by the driver to 2.4-V for fear of modulation nonlinearity. The optical carrier is generated from a continuous wavelength (CW) laser with 193.1-THz optical frequency, 100-kHz linewidth and 13-dBm output power. The optical signal generated with 3.8-dBm optical power is launched into the SMF for transmission. The dispersion parameter, attenuation, and nonlinear index of the SMF are 16.8-ps/nm/km, 0.2-dB/km, and 2.6×10^{-20}-m^2/W, respectively. Following the fiber transmission, a low-noise erbium-doped optical fiber amplifier (EDFA) with a constant output optical power of 10-dBm and noise figure of 3 is used to compensate the fiber loss. A variable optical attenuator (VOA) is utilized to adjust the received optical power, followed by a PIN photodiode (PD) with 1-A/W responsivity and 10^{-12}-A/Hz$^{0.5}$ thermal noise for signal detection. It is CD rather than bandwidth limitation that is the parameter of interest, so a 21-GHz fourth-order Bessel electrical low-pass filter (LPF) is added at the receiver side only to simulate the system bandwidth limit. Finally, offline processing of the obtained signals is performed in MATLAB. Remaining DSP at the receiver side includes down sampling, retiming, synchronization, T-spaced FFE with decision-direct least mean square algorithm and decision and BER calculation.

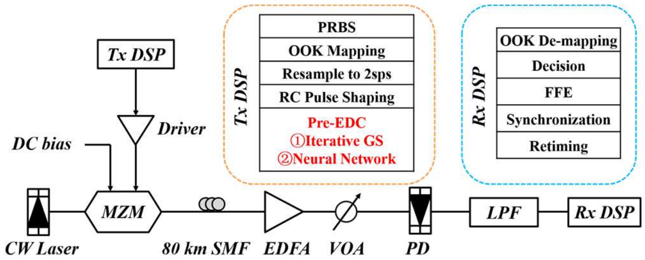

Fig. 4. Simulation and experimental set-up of the 56-GBaud OOK system 80-km SMF transmission

As illustrated in Fig. 4 (a, b), pre-compensated signals at the transmitter both displays different increases in peak-to-average power ratio (PAPR) values under NN equalization and under GS iteration. In contrast the transmit signal under NN based pre-EDC scheme is more severe, and thus the signal is normalized with a clipping operation when DC is 3, as shown in the Fig. 4 (c). Under optimal clipping, a clear improvement in BER performance can be observed when compared to the unclipped signals.

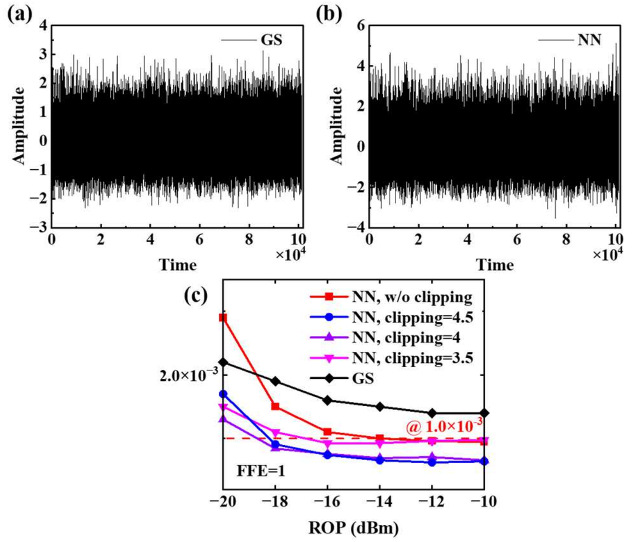

Fig. 3. Pre-compensated signals at the transmitter under (a) NN equalization and (b) GS iteration based based pre-EDC schemes. (c) Measured BER versus received optical power of 56-GBaud OOK signal over 80-km SMF transmission with different clipping operation in NN based pre-EDC scheme.

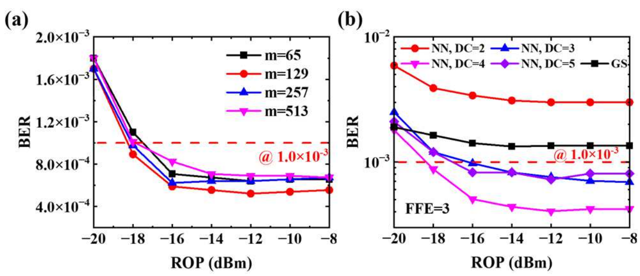

Fig. 5. Measured BER versus received optical power of 56-GBaud OOK signal over 80-km SMF transmission with different (a) number of neurons per hidden layer and (b) DC parameters in the DNN based pre-EDC scheme in comparison of the basic GS based pre-EDC scheme.

Fig. 5 (a) shows the Measured BER versus received optical power of 56-GBaud OOK signal over 80-km SMF transmission with different number of neurons per hidden layer. It can be seen that optimal hyper-parameters m should be set at 129 considering the BER performance and high complexity caused by DNN. The measured receiver sensitivity of the 56-GBaud OOK signal with different DC parameters in the DNN based and the basic GS based pre-EDC scheme is given out in Fig. 5 (b). The DNN based pre-EDC performs better when the DC is set at 4, under which the DC parameter match the bias of the MZM in the simulation system. It seems that the operation of clipping does not work when DC is larger, because the penalty of the increase in PRAR is neglectable when DC matches well. The OOK signal over 80-km SMF transmission can obtain the optimal BER of 4.2×10^{-4} at -8-dBm receiver optical power (ROP), below the threshold of 1.0×10^{-3} when the proposed scheme is applied. In comparison, BER of the basic GS pre-EDC scheme is 1.3×10^{-3} with the iteration number of 15. It is worth noting that there is only a 3-taps post-FFE at the receiver side. For the reason that the DNN is trained entirely for dispersion compensation, it then becomes less effective when the noise is significant but there is a noticeable BER performance improvement under low noise compared to the GS iterative algorithm.

IV. Conclusion

A novel performance enhanced pre-EDC scheme based on the DNN is proposed and demonstrated for a typical IM/DD system through simulation. We verify the proposed scheme in a 56-GBaud 80-km OOK system and the BERs of the basic GS with 15 iterations pre-EDC and proposed DNN pre-EDC schemes are 1.3×10^{-3} and 4.2×10^{-4} at -8-dBm ROP, respectively, with only a post-equalization of 3-taps FFE at the receiver side,. Our proposed scheme, based on the IM-DD structure, significantly enhances the system BER performance and is a potential candidate for 50-Gbps class 80-km metro optical networks, according to the simulation results.

Acknowledgment

This work is partly supported by the National Key R&D Program of China (2018YFB1800902); National Natural Science Foundation of China (U2001601, 62271517, 62035018); Local Innovation and Research Teams Project of Guangdong Pearl River Talents Program (2017BT01X121); National Natural Science Foundation of China under Grant 62001040.

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