Nonlinear Neural Network Equalizer for Metro Optical Fiber Communication Systems

Mahmoud M. T. Maghrabi, Shiva Kumar, and Mohamed H. Bakr

Department of Electrical and Computer Engineering
McMaster University, Hamilton, Ontario, L8S 4K1, Canada
maghrabm@mcmaster.ca, kumars@mcmaster.ca, mbakr@mcmaster.ca

Abstract **─**We present a neural network-based nonlinear electronic feed-forward equalizer. It compensates for the chromatic dispersion (CD) distortions in fiber optic communication systems with direct photo-detection. The proposed equalizer achieves bit error rate (BER) performance comparable to the maximum-likelihood sequence estimator (MLSE), with significantly lower computational cost. The complexity of the introduced equalizer scales linearly with the length of the inter-symbol interference (ISI) as opposed to exponential growth the MLSE complexity.

I. INTRODUCTION

Direct detected fiber-optic communication systems operating at 10 $Gbps$ and beyond suffer from severe ISI caused by CD [1]. Electronic dispersion compensation (EDC) techniques have been identified as cost-effective solutions to combat ISI and to guarantee speed, robustness, stability and adaptability [1]. Feed-forward equalizer (FFE) [1], decision feedback equalizer (DFE) [2] and MLSE [3] are most common amongst EDC techniques. Although the CD causes linear distortions to the received optical signal, they turn into nonlinear impairments in the electrical domain, due to the square law detection. As a result, linear equalizers, e.g., FFEs and DFEs, fail to compensate for these nonlinear distortions. Only nonlinear equalizers, e.g., MLSEs, can effectively mitigate these nonlinear impairments [4]. However, the MLSE suffers from its intensive computational cost that grows exponentially with the length of ISI span.

In this paper, we introduce a nonlinear FFE that is capable of compensating for the nonlinear distortions, with computational cost growing linearly with the ISI span. The proposed equalizer consists of single artificial neural network (NN) layer [5]. At first, the parameters of the NN are optimized using extensive training process considering all possible data combinations that will be transmitted through the optical channel. Then, this trained NN acts as a nonlinear filter whose impulse response inverts the nonlinear response of the optical communication channel.

II. CHANNEL AND EQUALIZER MODELS

The received optical field $r(t)$ of a metro fiber-optic communication channel is related to the transmitted optical modulated signal $x(t)$ as [1]:

$$r(t) = \left(x(t) * h_f(t)\right) * h_o(t), \qquad (1)$$

where the operation $*$ denotes convolution and $h_f(t)$ and $h_o(t)$ are the impulse responses of the fiber and the optical filter, respectively. $x(t)$ is the input optical field consisting of binary sequence $\{a_k\}$. The received optical field $r(t)$ is passed through a photo-detector, electrical low pass filter (LPF) and analog-to-digital converter with $1/T_s$ oversampling rate. The output electrical current at each sampled time $y_k = y(kT_s)$ is then given by:

$$y(kT_s) = \left(\left|r(kT_s)\right|^2 + n_e(kT_s)\right) * h_e(kT_s), \qquad (2)$$

where $h_e(t)$ is the impulse response of the electrical LPF and $n_e(t)$ denotes to the receiver noise. Due to linear distortions imposed by the channel $h_f(t)$ and the square-law detection, nonlinear ISI is introduced at the output signal $y(t)$. Therefore, a nonlinear equalizer is necessary to compensate for these nonlinear impairments and to recover the transmitted data effectively.

The model of the introduced nonlinear NN equalizer is shown in Fig. 1. Given an input kth vector $\boldsymbol{y}_k$ that contains n-samples corresponding to the current symbol and its interfering neighbors, kth output $\hat{X}_k$ of the equalizer is given as:

$$\hat{X}_k = \sum_{j=1}^{m} w_j^o f_h\left(\sum_{l=1}^{n} w_{jl}^h y_l\right), \qquad (3)$$

where n and m are the numbers of equalizer taps and hidden neural layer nodes, respectively. $f_h(\cdot)$ is the nonlinear activation function, w_{jl}^h is the weight assigned to the connection between lth input and jth node of the hidden layer, and w_j^o is the weight assigned to the connection between jth node of the hidden layer and the output layer node. These NN weights are optimized in the training process in order to minimize the difference between the equalizer output $\hat{X}_k$ and the transmitted data X_k.

Submitted On: September 8, 2018
Accepted On: October 3, 2018

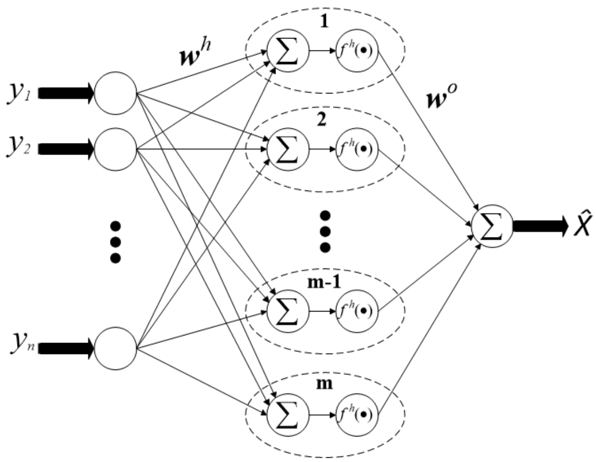

Fig. 1. The model of nonlinear neural network equalizer.

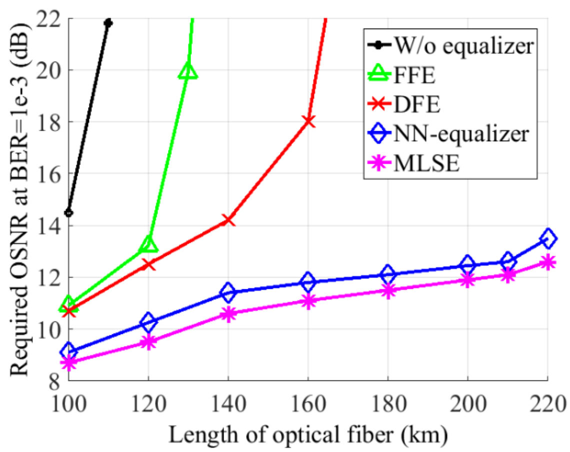

Fig. 2. The required OSNR at received $BER = 1 \times 10^{-3}$ versus fiber optic length. The performance without equalization is compared to the performance obtained using NN-equalizer with $n = 7$ and $m = 6$, FFE with 7-taps, DFE with 4-forward-taps and 3-backward-taps, and MLSE with 7-memory-size.

III. RESULTS

To evaluate the performance of the introduced equalizer, we consider a metro fiber-optic communication systems operating at $10\ Gbps$. The optical carrier is modulated by raised-cosine non-return to zero (NRZ) on-off keying (OOK). A single-mode fiber with dispersion coefficient of $17\ ps/nm/km$ is used in the system. The bandwidth of the optical and electrical filters are set as $50\ GHz$ and $7\ GHz$, respectively. In the Monte-Carlo simulation, pseudorandom binary sequence (PRBS) of length $2^{10} - 1$ is used to estimate BER. Total number of bits simulated $= 2^{14}$ bits. The parameters of equalizers are set as: $n = 7$, $m = 6$, and $f_h(\cdot) = \tanh(\cdot)$. Figure 2 shows the optical signal to noise ratio (OSNR) required to achieve a BER of 10^{-3} (sufficient for error-free operation with an advanced forward error correction) versus swept fiber-optic lengths. As can be seen, without equalization the maximum feasible transmission distance is limited to about $100\ km$. However, using the NN-equalizer this feasible distance is extended up to $200\ km$. Furthermore, in Fig. 2, we compare the performance of our NN-equalizer to the performance obtained using FFE, DFE and MLSE. It is clear that the linear equalizers (FFE and DFE) do not provide performance benefit since the channel (fiber channel + detection) is nonlinear. Although the MLSE slightly outperforms the NN-equalizer, it requires $128-$multiplication operations per bit. In contrast, our NN-equalizer needs only $42-$multiplication operations per bit. Hence, the NN-equalizer provides a better trade-off between performance and computational complexity.

IV. CONCLUSION

A nonlinear feed forward equalizer exploiting neural networks has been proposed to mitigate chromatic dispersion impairments of fiber-optic communication systems with direct detection. We show that the introduced equalizer extends the feasible transmission distance up to 200 km, whereas the distance is limited to about $100\ km$ in the case of no equalizer used. The introduced equalizer is shown to have performance comparable to performance achieved by MLSE, with much lower computational cost.

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