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Reservoir-computing and neural-network-based equalization for short reach communication

Francesco Da Ros, Stenio M. Ranzini, Yevhenii Osadchuk, Ali Cem, Bernard J. Giron Castro, and Darko Zibar
DTU Electro, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
fdro@fotonik.dtu.dk

Abstract: We review the use of neural-network-based equalizers for mitigating the power fading effect in intensity-modulated directly detected links, and compare the different approaches reported in the literature.

1. Introduction

As machine-to-machine communication within and between datacenters steadily grows, the demand for connectivity is answered by moving the systems to higher baudrates, pushing beyond 200 Gb/s/wavelength [1]. The low-cost and low-complexity requirements, however, do not yet justify the use of coherent technologies for short-reach communications, which mainly rely on intensity modulation and direct detection (IM/DD). This choice makes such systems highly sensitive to the impact of power fading effects caused by the combination of chromatic dispersion during transmission and square-law detection at the receiver side. Such an impairment becomes more significant as the signal bandwidth (transmission rate) increases, thus resulting in highly constrained transmission reach for high baudrate systems, even for O-band transmission [2]. In-line dispersion compensation, e.g. using fiber-brag grating, can mitigate the inter-symbol interference (ISI) but at the cost of reduced receiver power margin [3]. Linear feedforward equalizers (FFE) can partially compensate for the memory introduced by the power fading [2]; however, due to the nonlinear nature of the impairment, nonlinear equalizers, especially based on different neural networks (NN) architectures, have been extensively investigated recently.

In this work, we will review the main state-of-the-art NN-based techniques proposed in the literature for IM/DD system equalization.

2. System under investigation

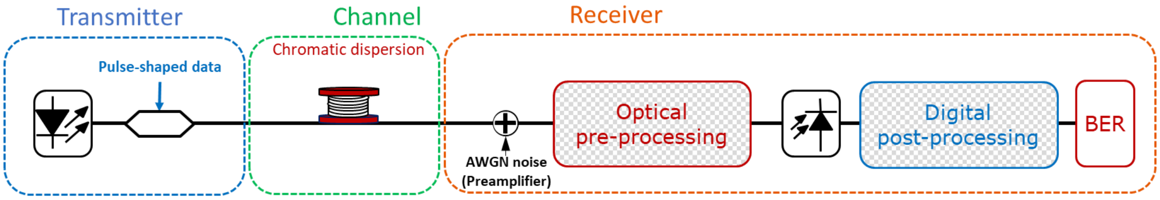

Fig. 1. High-level schematic of the IM/DD communication system under analysis.

The general structure of the IM/DD transmission system under investigation is shown in Fig. 1. The information bits are mapped to the desired modulation format and pulse shaped before being encoded onto the optical domain through a Mach-Zehnder modulator (MZM) which modulates the intensity of a continuous-wave optical carrier. The optical signal is then transmitted through a standard single-mode fiber (SSMF), where chromatic dispersion results in pulse broadening. The signal is detected by a photodetector (PD) on the receiver side, followed by digital signal processing for equalization. Noise is here added before the PD by considering a pre-amplified receiver. Alternatively, the use of a transimpedence amplifier would result in only minor changes in the noise statistics. An additional pre-processing stage in the optical domain (before photodetection) is also considered.

3. Neural-network based equalizers for IM/DD

The use of feedforward NNs (FNN) for equalization has been firstly considered by including memory at the input layer (time-delay FNN, TD-FNN) [4-8]. An example of TD-FNN is shown in Fig. 2(a), where a sliding window consisting of multiple received time samples is fed into the input layer of the FNN. Beyond TD-FNNs, using NN which inherently includes memory, such as recurrent NN (RNN) in various flavors, has been considered. Reports in literature include conventional RNNs [9-10], gated recurrent units (GRUs) [11], and long-short-term memory (LSTMs) [12]. All structures (LSTM shown in Fig. 2(b)) include recurrent connections in the hidden layers providing inherent memory to the equalizer. The training of TD-FNN increases in complexity linearly with the required memory (size of the input layer), whereas the training of RNNs may be hindered by vanishing gradients and is generally relatively complex due to the need to back-propagate through time. Therefore, from the perspective of a need for a periodic retraining due to changing channel conditions, e.g. laser frequency and power drifts, offset filtering, etc., an alternative architecture, namely reservoir computing (RC) has been investigated recently. Reservoir computing consists of a highly redundant RNN where only the connections to the output layer are trained and the input and hidden weights are initialized randomly and kept fixed (Fig 2(c)). This choice allows for a single-step training stage by applying e.g. Tikhonov regularization [13]. Reports in the literature have been considering either digital RC [13,16,17] or moving part of the complexity in the optical domain with optoelectronics RC [14,15]. The use of optoelectronics approaches could provide an advantage in terms of power consumption, however, the two main proposed schemes (on-chip photonic RC [14] and delay-based RC [15]) face challenges in terms of fabrication tolerances (precise delay tuning, [14,15]) and operating speed (upsampling required for masking [15]). Finally, more recently, optical pre-processing with specially designed receiver front-ends has been considered to provide a more suitable signal in input to the equalizer. Optical pre-processing, mainly consisting of spectral slicing, has been proposed in combination with digital equalizers for sharing complexity between optical and digital domains: micro-ring resonator-based filters with FFEs [18], Mach-Zehnder delay interferometers with TD-FNNs [13] and array waveguide gratings with TD-FNNs or RC [16].

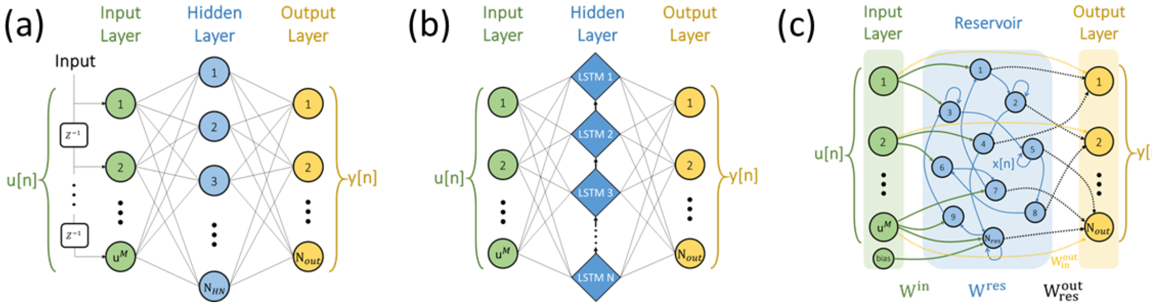

Fig. 2. Architectures of TD-FNN (a), LSTM RNN (b), and RC (c)

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