Deep Reservoir Computing for 100 Gbaud PAM6 IM/DD Transmission Impairment Mitigation

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Abstract: We experimentally evaluate a deep Reservoir Computing (RC)-based post-equalization for 100 Gbaud PAM6 IM/DD transmissions. It achieves ~1 dB higher sensitivity than DFE, and ~50% implementation complexity reduction compared with the conventional RC configuration.

1. Introduction

The rapid growth of data center traffic has imposed stringent requirements on almost all aspects of optical interconnect technologies to support the upcoming 800 Gb/s and 1.6 Tb/s Ethernet [1]. Currently, intensity-modulation and direct detection (IM/DD) systems with 200 Gb/s/lane rate are still considered strong candidates for SR, DR, and FR applications of up to 2 km coverage, either with parallel fibers or wavelength-division multiplexing (WDM) [2]. Considering energy consumption and footprint requirements, these systems will preferably operate with monolithically integrated transceivers, e.g., VCSELs, directly-modulated lasers, and externally modulated lasers (EMLs), and preferably without any optical amplification [3]. However, despite operating at the O-band, the chromatic dispersion (CD) induced power penalty on the side channels of either LAN-WDM4/8 or CWDM4/8 configurations arises as a critical issue at high baud rates [4]. Such an issue can be tackled by increasing the system power budget with higher output power from the transmitter and/or higher receiver sensitivity or sophisticated mitigation methods in either the analog or the digital domain [5]. Digital signal processing (DSP) algorithms, such as feedforward equalizer, decision-feedback equalizer (DFE), maximum likelihood sequence estimation, and nonlinear equalizations with Volterra-series, etc., have been well-studied and often used to mitigate short-reach transmission impairment, i.e., CD induced power penalty, limited-bandwidth, modulation nonlinearity, etc. Recently, the research community has also turned to machine learning techniques, which bring opportunities to generate new knowledge in application to combat fundamental and practical challenges in optical communications [7]. Among various tools, Reservoir Computing (RC) is identified as a hardware-friendly approach to providing equalization with low complexity [8].

In this work, we experimentally evaluate a deep RC-based post-equalization approach for mitigating 100 Gbaud 6-level pulse amplitude modulation (PAM6) transmission impairment. The performance of the deep RC is studied and benchmarked against the conventional DFE and the shallow RC scheme implemented in Ref. [8]. The results show that the deep RC approach achieves about 1 dB received optical power (ROP) sensitivity improvement in both back-to-back (B2B) and 200-m single-mode fiber (SMF) links compared with the DFE. In addition, the proposed deep RC provides approximately 50% implementation complexity reduction without degrading bit error rate (BER) performance, compared with the shallow RC configuration.

2. Deep reservoir computing

Figure 1 shows the architecture of a deep RC with multiple reservoir layers stacked on top of each other. The reservoir state for each layer is updated by the following equation [9]:

$$x_l(n) = \begin{cases} \tanh\left(W_{in,1}u(n) + \theta_1 + W_1 x_1(n-1)\right) & l = 1 \\ \tanh\left(W_{in,l}x_{l-1}(n) + \theta_l + W_l x_l(n-1)\right) & l > 1 \end{cases} \tag{1}$$

where $x_l(n)$ is the output for the lth layer, $u(n)$ is the input for the first layer, and θ_l is the bias for the lth layer. $W_{in,l}$ is

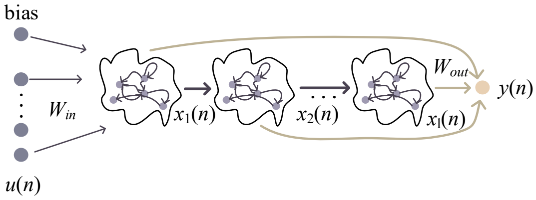

Fig. 1. The deep RC architecture.

the input weight for the lth layer and is selected with a uniform distribution over [-α, +α], where α is the scale factor. The recurrent weight W_l for the lth layer is randomly assigned from a uniform distribution and re-scaled according to the spectral radius ρ. The output of the deep RC is:

$$y(n) = W_{out}\left[x_1(n)x_2(n)x_3(n)...x_{NL}(n)\right] + \theta_{out} \tag{2}$$

where W_{out} is the readout weight of deep RC, which is determined in the training phase and fixed in the testing phase. θ_{out} is the bias-to-reservoir weight vector for layer l. Note that the shallow RC can be achieved by setting $l = 1$.

3. Experimental setup

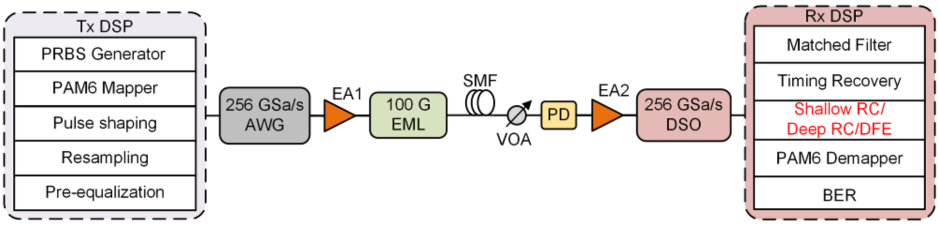

Fig. 2. The experimental setup and DSP routine in the transceiver.

Figure 2 shows the experimental setup for the 100 Gbaud PAM6 IM/DD transmission. The transmitted PAM6 symbols are mapped from a random binary sequence of >1 million bit length obtained using the Mersenne Twister generator with a shuffled seed number. The PAM6 symbols are pulse-shaped by a root-raised-cosine filter with a 0.02 roll-off factor. Then, the PAM6 symbols are re-upsampled to match the sampling rate of the arbitrary waveform generator (AWG, 256 GSa/s, M8199A, Keysight). Frequency domain pre-equalization up to 70 GHz is used to compensate for bandwidth limitation in the system. After that, the output of the AWG signal is amplified by a 65-GHz electrical amplifier (EA1). A 100-GHz Class C-band EML is used as an optical transmitter [10]. After 200-m SMF transmission, the ROP is adjusted by a variable optical attenuator (VOA) before being sent to a p-i-n photodiode (PD, 3 dB Bandwidth > 90 GHz and responsivity = 0.5 A/W). It is worth noting that no optical amplifier was used in our IM/DD setup. The output of the PD is amplified by a second EA (65 GHz) and sampled with a 256 GSa/s real-time digital storage oscilloscope (DSO, UXR1104A Infiniium UXR-Serie, Keysight). In the receiver DSP routine, three types of post-equalization schemes, namely, DFE, shallow RC, and deep RC, are used to mitigate the link impairment, respectively. The DFE configured with 55 feedforward taps and 13 feedback taps is used as a benchmark. The shallow RC and the deep RC are configured with the same total number of reservoir units for comparison, i.e., 80 reservoir units in the shallow RC, and 4 layers of 20 reservoir units per layer in the deep RC.

4. Results and Discussion

The 100 Gbaud PAM6 performances for B2B and 200-m SMF transmission are evaluated. We use the 6.25% overhead (OH) hard-decision forward error correction (HD-FEC) threshold of 4.5×10^{-3} for the BER result analysis. In Fig. 3(a) and (b), we show the BER as a function of ROP for B2B case and 200-m SMF transmission. Without any impairment compensation scheme, we cannot obtain the BERs below the HD-FEC threshold. Compared with the conventional DFE, both RC methods offer about 1 dB ROP sensitivity improvement at HD-FEC in both B2B and 200-m SMF links. The deep RC and shallow RC have comparable performance. The eye diagrams for 100 Gbaud PAM6 are shown in Fig. 3(c). Figure 3(d) shows the relationship between the reservoir units and the number of weights. The number of weights indicates the implementation complexity, i.e., multiply operation, generation and storage of weights, etc. One can observe that the number of weights of shallow RC grows

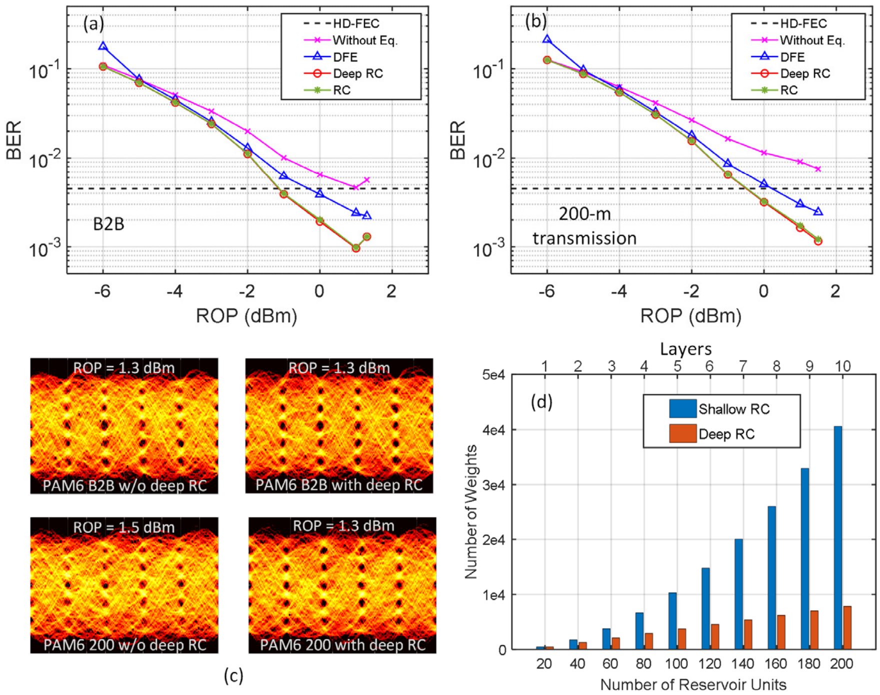

Fig. 3. BER versus ROP for (a) B2B and (b) 200-m SMF transmission. (c). The eye diagrams of 100 Gbaud PAM6 in B2B and 200-m SMF transmission cases with and without deep RC. (d). The number of weights and the number of reservoir units in the shallow RC and deep RC configurations, respectively.

exponentially when the reservoir units are larger than 80. Compared with the shallow RC scheme, the deep RC achieves an approximately 50% reduction of implementation complexity without degrading BER performance.

5. Conclusion

We have preliminarily studied a deep RC-based post-equalization scheme with a 100 Gbaud PAM6 optically-unamplified IM/DD link. The results show that the deep RC outperforms the conventional DFE in both B2B and 200-m SMF link with about 1 dB sensitivity improvement. The deep RC and shallow RC have comparable BER performance, whereas the hardware requirement of weights generation and storage in deep RC is significantly reduced. It is expected that deep RC, once implemented in analog or hybrid analog/digital domain co-integrated with transceiver photonics/electronics, can become an effective solution for the link impairment mitigation for high baud rate optical interconnects beyond the next generations.

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7. References

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