# Cascade Recurrent Neural Network Enabled 100-Gb/s PAM4 Short-Reach Optical Link Based on DML

**Zhaopeng Xu[1], Chuanbowen Sun[1], Tonghui Ji[1,2], Honglin Ji[1], and William Shieh[1]**
[1] *Department of Electrical and Electronic Engineering, The University of Melbourne, Parkville, VIC 3010, Australia*
[2] *School of Computer Science and Communication Engineering, University of Science and Technology Beijing, Beijing 100083, China*
*zhaopeng@student.unimelb.edu.au*

**Abstract:** A cascade RNN-based equalizer is proposed which outperforms traditional NN-based equalizers for short-reach optical links. A cascade RNN-enabled 100-Gb/s PAM4 link is experimentally demonstrated over 15-km fiber using a 16-GHz DML in C-band. © 2020 The Author(s)
**OCIS codes:** (060.2330) Fiber optics communications; (200.4260) Neural networks

## 1. Introduction

Driven by the exponential growth of cloud and mobile services, there is an increasing demand for high-speed low-cost short-reach communication systems such as data center interconnect. Intensity modulation and direct detection (IM/DD) optical links are well-suited for such applications due to its low-cost and simple structure [1]. In terms of cost, IM/DD links with direct modulated lasers (DML) are more favorable compared with those using Mach-Zehnder modulators (MZM) or electro-absorption modulated lasers (EML). However, the cost-effective direct detection systems face many challenges, including (i) the nonlinearity induced by the mixture of chromatic dispersion (CD) and the square-law direct detection operation, and (ii) the power fading when the product of signal baud-rate and transmission distance is large [2]. Furthermore, the bandwidth deficient device used is also a key limiting factor that causes signal distortion and severely deteriorates the system performance. Pre- and post-equalization methods are used in [3,4] to mitigate the destructed spectrum, however these methods require digital signal processing (DSP) on both transmitted and received signals with a measured channel response in advance. With the rapid development of machine learning technologies, various types of neural networks are employed as efficient end-to-end equalizers at the receiver in different short-reach scenarios in recent years, for example, feedforward NNs (FNN) used in [5, 6], and recurrent NNs (RNN) employed in [7].

In this paper, we experimentally demonstrate a 100-Gb/s pulse amplitude modulation (PAM)-4 short-reach direct detection system over 15-km standard single mode fiber (SSMF) using a 16-GHz DML in C-band with only post-equalization. A novel cascade RNN based equalizer is proposed, which enables the transmission of 100-Gb/s PAM4 signals with band-limited devices. The computational complexity of cascade RNN-based equalizers is also analyzed and compared with other NN-based equalizers. The proposed cascade RNN-based equalizer can further improve the system bit-error-rate (BER) performance compared with FNN or RNN-based equalizer, with limited number of additional multiplications needed. With the help of cascade-RNN based equalizer, the system BER can be lower than the 7% hard-decision forward error correction (FEC) threshold when the received optical power is 5 dBm.

## 2. Cascade NN- and cascade RNN-based equalizers

The schematic of a 2-layer cascade NN is shown in Fig. 1(a) and a 2-layer cascade RNN is shown in Fig. 1(b). The main difference between traditional NNs and cascade ones is that the cascade networks include connections from the input and every previous layer to the following layers (shown as the pink arrows). As shown in Fig. 1, the $i$-th layer consists of $n^{[i]}$ neurons, where $i=0,1,2$ ($n^{[2]}=1$ in the figure). For the $i$-th layer, the weight matrix $\mathbf{w}^{[i]}$ is an $n^{[i]} \times n^{[i-1]}$ matrix containing all the weights connected from the ($i$-1)-th layer to the $i$-th layer, the bias matrix $\mathbf{b}^{[i]}$ is an $n^{[i]} \times 1$ matrix containing all the biases and $f^{[i]}(\cdot)$ is the activation function. For cascade RNN, the weight matrix

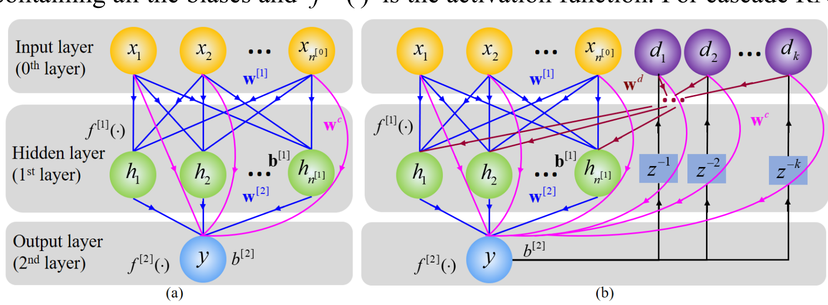


Fig. 1. Schematic of a 2-layer cascade NN (a), and a 2-layer cascade RNN (b).

$\mathbf{w}^d$ is an $n^{[1]} \times k$ matrix assuming $k$ delays are employed in the feedback loop, and $\mathbf{w}^c$ is an $1 \times (n^{[0]} + k)$ matrix controlling the connection of the cascade structure. Assuming all the weights and biases are known through training, the one-time forward propagation (FP) (also refer to the symbol equalization step) for F-NN can be expressed as

$$\mathbf{H}^{[1]} = f^{[1]}([\mathbf{w}^{[1]}, \mathbf{w}^d][\mathbf{X}^T, \mathbf{Y}_d^T]^T + \mathbf{b}^{[1]}), \tag{1}$$

$$y = f^{[2]}([\mathbf{w}^{[2]}, \mathbf{w}^c][\mathbf{H}^{[1]T}, \mathbf{X}^T, \mathbf{Y}_d^T]^T + b^{[2]}), \tag{2}$$

where $\mathbf{H}^{[1]}$ is an $n^{[1]} \times 1$ matrix consisting of the output value of the hidden layer, $\mathbf{X}$ is the input vector containing $n^{[0]}$ inputs, $\mathbf{Y}_d$ is the input vector containing $k$ feedbacks and y is the output. From Eqs. (1) and (2), the number of multiplications needed to recover 1 symbol using cascade RNN, denoted $N_{mul}$, is given by

$$N_{mul} = (n^{[0]} + k + 1)n^{[1]} + n^{[0]} + k, \tag{3}$$

where the computational complexity of the activation function is omitted and a look-up table is assumed. Significant BER improvement can be achieved using the cascade structure because it provides a direct linear mapping between the inputs and the output, which contributes greatly to the overall equalization process.

## 3. Experimental setup and results

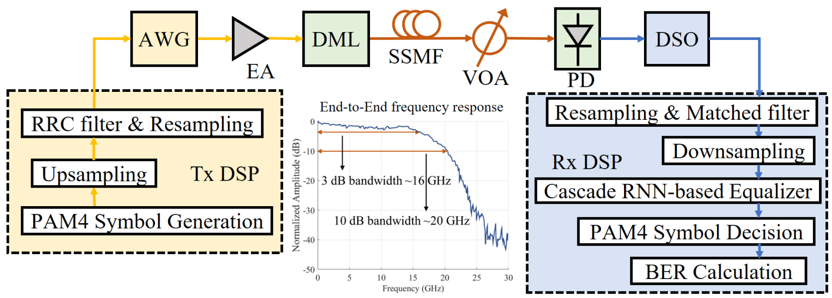


Fig. 2. Experimental setup of the 100-Gb/s PAM4 optical link using DML. Inset: End-to-end channel response.

The experimental setup of a DML-based PAM4 short-reach direct detection optical link is shown in Fig. 2. The 100-Gb/s PAM4 signal is generated by an arbitrary waveform generator (AWG, Keysight M8196A) with a sampling rate of 92 GSa/s and a root raised cosine (RRC) filter with roll-off factor of 0.1 is used for Nyquist PAM4 pulse shaping. After resampling, an electrical amplifier with 17 dB gain (SHF 100 BP) is employed to amplify the electrical PAM4 signal. Then the amplified signal is fed into a DML biased at 55 mA and transmitted over a 25-km SSMF. The output power of DML is 9.5 dBm. At the receiver, a variable optical attenuator (VOA) is used to adjust the received optical power (ROP) and a 43-GHz photodetector (PD, BPDV2150R) is employed to detect the optical signal. The detected signal is captured by a digital storage oscilloscope (DSO, DSA-X 93304Q) with a sample rate of 80 GSa/s. The end-to-end frequency response is shown as the inset of Fig. 2 where the 3-dB bandwidth of the system is only around 16 GHz limited by the DML, which causes severe signal distortion. After resampling, matched RRC filtering and downsampling, the received PAM4 symbols are fed into the cascade RNN-based DSP module for nonlinear equalization and BER calculation. In the cascade RNN-based equalizer, the NN input sequence is a column vector containing the current symbol, $(n^{[0]} - 1)/2$ past symbols, and $(n^{[0]} - 1)/2$ post symbols. The number of outputs is selected as 1 which is the predicted value of the current symbol. Tanh activation function is employed in the hidden layer while the pure-linear function is employed in the output layer. 20000 PAM4 symbols are used to train different

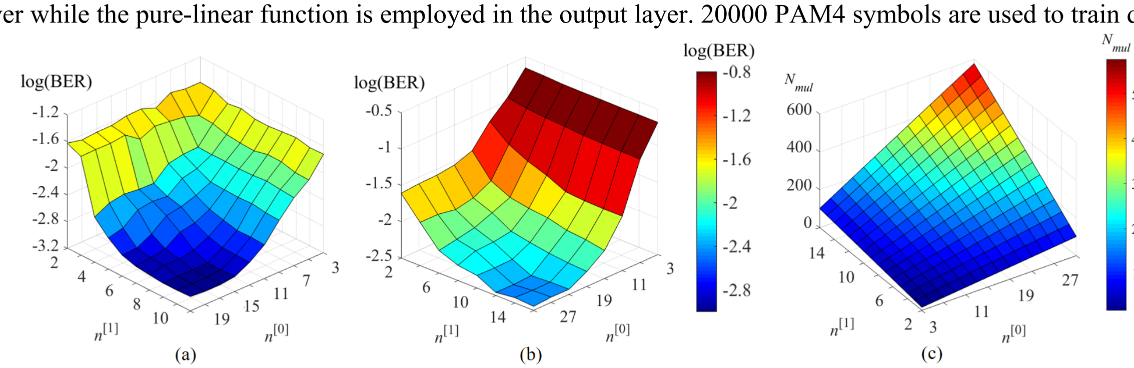


Fig. 3. BER of 50-Gb/s PAM4 transmission over 25-km fiber (a), BER of 100-Gb/s PAM4 transmission over 15-km fiber (b), and the number of multiplications $N_{mul}$ (c) versus different $n^{[0]}$ and $n^{[1]}$.

NNs and another 1.2 million PAM4 symbols are used to perform nonlinear equalization and BER calculation.

Figure 3(a) shows the BER versus $n^{[0]}$ and $n^{[1]}$ of 50-Gb/s PAM4 over 25-km fiber when the ROP is -1 dBm and Fig. 3(b) shows the BER of a 100-Gb/s PAM4 over 15-km fiber when the ROP is 5 dBm. Besides the 100-Gb/s experiment, a 50-Gb/s PAM4 transmission is also carried out to show results without the limitation of DML bandwidth. The parameter $k$ is optimized and set as 2. For 100-Gb/s PAM4 transmission, no further BER improvement is observed when $n^{[0]}$ is beyond 23 and $n^{[1]}$ beyond 12, since 23 inputs contain enough information about the signal distortion and 12 hidden neurons are also sufficient for NN to perform nonlinear equalization. Additional inputs and hidden neurons may introduce unnecessary weights and biases with little contribution to the BER performance. For 50-Gb/s PAM 4transmission, the NN size for a converged BER can be reduced, where only 15 inputs and 9 hidden neurons are enough to achieve the best BER performance. Though the transmitted fiber length of 100-Gb/s PAM4 (15-km) is shorter than that of 50-Gb signals (25-km), the severe power fading and strong bandwidth-limiting effects of the DML brings in much significant signal distortion to the 100 Gb/s signal, which requires larger NNs to deal with. Figure 3(c) illustrates the $N_{mul}$ when different $n^{[0]}$ and $n^{[1]}$ are used, and we can see that $N_{mul}$ is more sensitive to $n^{[1]}$ compared with $n^{[0]}$. There is always a trade-off between BER and computational complexity and we can refer to Fig. 3 to select NNs that satisfy different requirements.

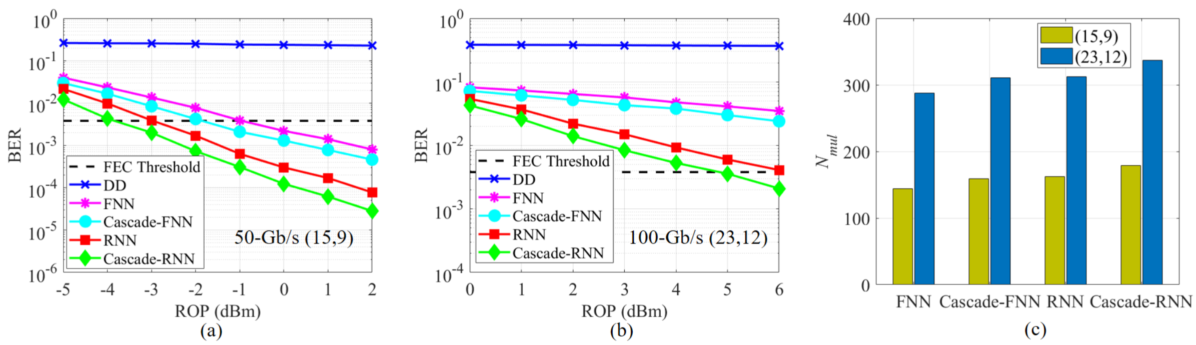


Fig. 4. BER versus ROP using different NN-based equalizers of 50-Gb/s PAM4 transmission over 25-km fiber (a), 100-Gb/s PAM4 transmission over 15-km fiber (b), and the number of multiplications $N_{mul}$ of different types of NNs with (15,9) or (23,12) (c).

System BER versus ROP using FNN-, cascade FNN-, RNN-, and cascade RNN-based equalizers of 50-Gb/s and 100-Gb/s PAM4 links are shown in Figs. 4(a) and 4(b) respectively. The BER performance of direct detection (DD) is also presented as a comparison. A (15,9) NN is used for 50-Gb/s transmission and a (23,12) NN is employed for the 100-Gb/s case in terms of computational complexity. Here we use $(n^{[0]}, n^{[1]})$ to represent the parameters of 2-layer NNs. Cascade RNN-based equalizers outperform the others, and we can clearly see the improvement of BER with the help of both cascade and recurrent structure (BER performance: Cascade-RNN>RNN>Cascade FNN>FNN). This cascade and recurrent structure of NNs can explore the most of system BER performance when simply increasing $n^{[0]}$ and $n^{[1]}$ does not make any sense, since the cascade structure provides additional paths to determine linear relationship and the recurrent one introduce almost accurate predictions of past symbols. With the help of cascade RNN, the receiver sensitivity can be increased to -4 dBm for 50-Gb/s signal considering the 7% FEC threshold, with 3 dB improvement compared with using traditional FNN. When the bit-rate increases to 100-Gb/s, cascade RNN can achieve a receiver sensitivity of 5 dBm, with about 1 dB improvement compared with RNN, where FNN and cascade FNN can not support to achieve BER under the 7% FEC threshold. Figure 4(c) depicts $N_{mul}$ of different types of NNs with (15,9) or (23,12). Only 24.3% or 17.0% more of computational complexity is needed for cascade RNN compared with FNN, which indicates the potential of real-time implementation.

## 4. Conclusion

In this paper, we experimentally demonstrated a 100-Gb/s PAM4 short-reach optical link via a 15-km fiber using a 16-GHz DML in C-band with only post-equalization. A cascade RNN-based equalizer is proposed to effectively compensate signal distortion, which show better BER performance than FNN or RNN-based equalizers. With the aid of cascade RNN, BER lower than 7% FEC threshold can be achieved when the receiver sensitivity is above 5 dBm.

## 5. References

[1] Q. Zhang, et al., Opt. Lett. **41**, 4449-4452 (2016).
[2] K. Zhong, et al., Opt. Express **23**, 1176–1189 (2015).
[3] R. Hirai, et al., in Proc. OFC (2015), paper TH4A.6.
[4] F. Li, et al., in Proc. OFC (2019), paper Tu2F.4.
[5] J. Estaran, et al., in Proc. ECOC (2016), paper M.2.B.2.
[6] Z. Wan, et al., Opt. Express **26**, 10631-10642 (2018).
[7] C. Ye, et al., in Proc. ECOC (2018), paper Mo4B.