Efficient Equalization of Non-equally Spaced Multi-level Signal by Piecewise Linear Equalizer

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***Abstract*—We propose to utilize a piecewise linear equalizer to efficiently correct the non-equidistant PAM signals caused by the nonlinear modulation of Mach-Zehnder modulators, with which the BER is reduced by an order of magnitude.**

Keywords—piecewise linear equalizer, modulation, nonlinear equalization, digital signal processing

I. Introduction

Intensity modulation and direct detection (IM/DD) systems have dominated the cost-sensitive applications such as passive optical network (PON) and datacenter interconnect for decades, owing to their low cost, small footprint and low latency [1-3]. To cope with the insatiable demand for capacity and the limited device bandwidth, multi-level modulation formats, such as pulse amplitude modulation (PAM) are replacing the conventional binary format nowadays. However, despite the enhanced spectral efficiency, the generation and detection of multi-level signaling requires digital-to-analog and analog-to-digital converters, respectively, which inevitably increases the cost.

Another challenge of the multi-level signaling technique is the high linearity requirement on the components in the system, including the RF amplifier, modulator, and photo-detector. This is even challenging in the next-generation PON and 800G/1.6T interconnect, where high-bandwidth electro-absorption modulated laser (EML) and Mach-Zehnder modulation (MZM) are commonly employed. Both of them suffer from the nonlinear modulation curve. For example, EML's modulation curve follows exponential shape, while MZM has a sinusoidal transmittance curve. Maintaining the swing of driving signal within a small range can alleviate this issue, however, this tradeoff technique becomes more and more unacceptable because the low system margin of these ultra-high baud-rate system requires a considerable extinction ratio of the transmitter to assure a better receiver sensitivity. This makes the modulation of multi-level PAM signals inevitably fall into the nonlinear region of these transmitters.

Pre-compensation can be performed with lookup table [4-5] to resolve this issue, but the flexibility could be a problem to accommodate for diverse characterizations of the transmitters from various vendors as well as the various and dynamic configurations in the systems. Adaptive equalization at the receiver side is thus more preferable. However, the compression in the modulation levels incurs strong nonlinearity, especially when modeled with polynomial series. Linear equalizer such as feedforward equalizer (FFE) or decision-feedback equalizer (DFE) cannot equalize this nonlinear effect. Recent reports on using Volterra equalizer [6] and machine learning techniques [7] to solve this issue consume too many hardware resources, which is inefficient thus not suitable for the cost-sensitive scenarios.

In this paper, we propose to utilize piecewise linear (PWL) equalizer [8-9] to correct the non-equally spaced modulation levels more efficiently. We experimentally demonstrate the PWL scheme can reduce the bit error ratio (BER) by almost one order of magnitude for highly compressed 56-Gb/s PAM4 signal generated by MZM with very low computation complexity. Our analysis confirms that the computational complexity of the PWL is only one third of the pruned nonlinear 3rd-order Volterra equalizer with even better BER performance.

II. Principle of Operation

When the MZM is used to modulate a multi-level signal with large extinction ratio, its nonlinear modulation curve will compress the signal levels close to the peak and valley of the transmittance, as illustrated in Fig. 1(a). This will reduce the minimum Euclidean distance of the received signal and cause significant BER penalty. A linear equalizer cannot compensate for this nonlinear effect. However, if we use the polynomial model to characterize this nonlinearity, such as the Volterra series, the polynomial order could be very high, which is not efficient.

Considering this specific feature of compression, the piecewise linear (PWL) equalizer could be more suitable to solve this issue. The PWL equalizer consists of three steps, including signal threshold decomposition, multiple linear filters and linear addition, as illustrated in Fig. 1(b). In the first step, threshold decomposition expansions can be applied to the linear combiner with a set of thresholds. N thresholds will decompose the waveform into $N+1$ parts. For example, when the thresholds are set as $\tau = \{\lambda_1, \lambda_2, \ldots, \lambda_N\}$, then the waveform will be divided into $I_1 = (-\infty, \lambda_1)$, $I_2 = [\lambda_1, \lambda_2)$, …, and $I_{N+1} = [\lambda_N, +\infty)$. Then, linear equalizations are performed with each part and the outputs of all parts are summarized together as the PWL's output. The coefficients of all linear equalizers are updated together with a common error signal obtained from the PWL's output by the least mean square algorithm. The decomposition process in the PWL equalizer brings a strong nonlinearity to the signal but with very low implementation cost, in which only a few comparators are needed. Thus, the PWL equalizer can provide an effective and efficient solution for the non-equidistant level spacing problem.

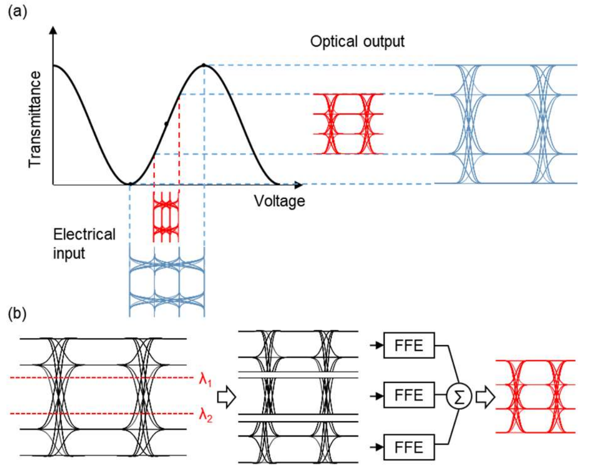

Fig. 1. (a) MZM transmission curve; (b) threshold decomposition, separate equalization, and the summation of PAM4 signal by PWL equalizer.

III. Experiments and Results

Figure 2 shows the experimental setup of 56-Gbit/s PAM4 transmission system. At the transmitter, a 28-Gbaud PAM4 signal is generated by an arbitrary waveform generator (AWG) operating at 56 Gsample/s. The electrical PAM4 signal is first amplified by an electrical amplifier (EA) with 20-dB gain and then used to modulate the continuous wave centered at 1550 nm via an MZM. It is worth noting that we utilize C-band laser here due to the lack of O-band light source in our laboratory. Therefore, we also add a piece of dispersion compensation fiber (DCF) to remove the effect of fiber chromatic dispersion, to emulate the fiber transmission with O-band laser. Then, the optical signal is launched into 20-km standard single-mode fiber (SSMF), followed by the DCF module capable of compensating for chromatic dispersion of ~320 ps/nm. At the receiver, a variable optical attenuator (VOA) is used to adjust the received optical power (ROP) of the signal. Then, a PIN photo-diode (PD) is used to convert the received light signal into an electrical signal. The received signal is amplified by another EA and eventually sampled by a digital storage oscilloscope (DSO) with a sampling rate of 80 Gsample/s. Finally, offline signal processing including resampling, clock recovery, synchronization and equalization is carried out to calculate bit error rate with >1 million bits.

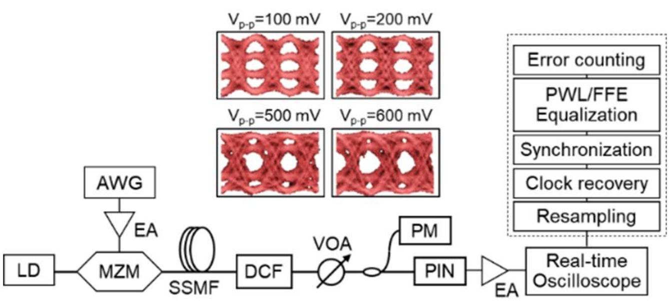

Fig. 2. Experimental setup. AWG: arbitrary waveform generator; LD: laser diode; MZM: Mach-Zehnder modulator; EA: electrical amplifier; SSMF: standard single mode fiber; DCF: dispersion compensation fiber; VOA: variable optical attenuator; PM: power meter.

First, we optimize the thresholds of the PWL equalizer. For the simplicity, we only consider two thresholds in our PWL equalizer, i.e., the threshold set is $\tau = \{\lambda_1, \lambda_2\}$. This requires three parallel feedforward structures. After normalization, the signal levels are within the range of [-3, 3]. Thus, we sweep λ_1 and λ_2 values both from -3 to 3 with a step of 0.2 to find the optimal threshold set for the case of 56-Gbit/s in the back-to-back (BTB) transmission. The swing of driving signal to the EA is 700 mV, the ROP is 0 dBm, and the number of taps in each parallel equalizer are all 17. Figure 3(a) shows the BER performance at various combinations of thresholds. It is clear that λ_1 and λ_2 are almost symmetric with zero, which can be attributed to the symmetry of the modulation curve of the MZM. Finally, the optimal threshold is found to be {-1, 1.2}, with which the minimum BER of 3.70×10^{-4} is achieved. Here, the eye diagram of the equalized signal is shown in Fig. 3(c). The non-equal space before the equalization [as shown in Fig. 3(b)] is compensated efficiently with the PWL equalizer. However, the conventional FFE equalizer fails to solve this non-equal space issue even with three times of number of taps as the eye diagram in Fig. 3(d) reveals. Figure 3(b)-(d) also show that a slight time skew in the eye diagram is compensated by the PWL equalizer.

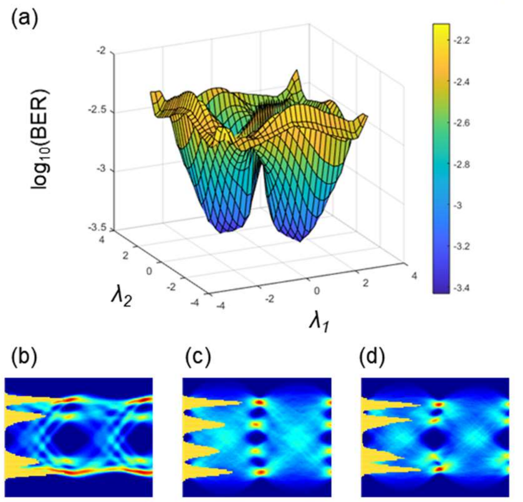

Fig. 3. (a) 3D colormap surface of BER performance versus threshold sets λ_1 and λ_2 of PWL equalizer. The eye diagrams and histograms of the signal (b) before equalization, (c) after PWL equalization, and (d) after FFE equalization.

We then compare the BER performance of the conventional FFE and the PWL equalizer for the non-equally spaced PAM4 signal. The number of taps in the FFE is optimized to be 51. For the fair comparison, the PWL employs 17 taps in each parallel equalizer. The thresholds of the PWL need optimization under different swing of driving signals. In the BTB case, the receiver sensitivity gets improved when the swing of driving signal is increasing from 100 mV to 400 mV (linear region of MZM modulation), and becomes worse when the swing is larger than 500 mV (nonlinear region of MZM modulation). The eye diagrams of the signal with swing >500 mV exhibit apparent compression at the upper and lower levels. Therefore, the nonlinear distortions cancel out the performance improvement by high extinction ratios. The FFE can only equalize the overall response while does no help to the level-dependent distortions. This can be seen from the eye diagram after FFE. On the other hand, the PWL can not only have the similar performance as FFE in the linear region, but also correct the non-equally spaced levels and achieve better BER. For example, the BER@2 dBm when the RF swing is 700 mV is reduced from 3.99×10^{-3} to 4.09×10^{-4}. It is worth noting that the ability of correcting the non-equally spaced levels of the PWL is not infinite. When the swing of the driving signal is too large, i.e., the compression is too strong, the performance improvement owing to the PWL is also limited.

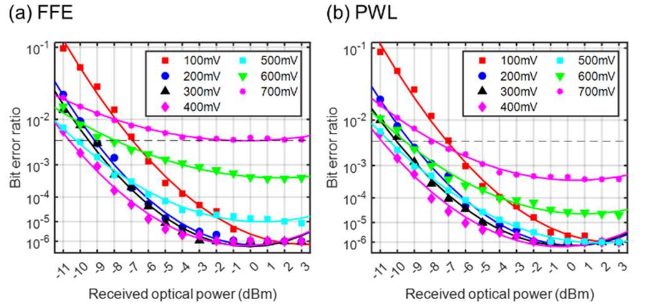

Fig. 4. BER performance of the 56-Gbit/s PAM4 signal using FFE equalizer and PWL at BTB.

After 20-km SSMF transmission, the maximum ROP is only -5 dBm due to the large insertion loss of the fiber and the DCF module (8 dB in total). Nevertheless, the BER performance improvement by the PWL equalizer is still significant, as shown in Fig. 5. The BER@-5 dBm when the RF swing is 700 mV is reduced from 3.55×10^{-3} to 1.01×10^{-3}. This agrees well with the BTB results in Fig. 4.

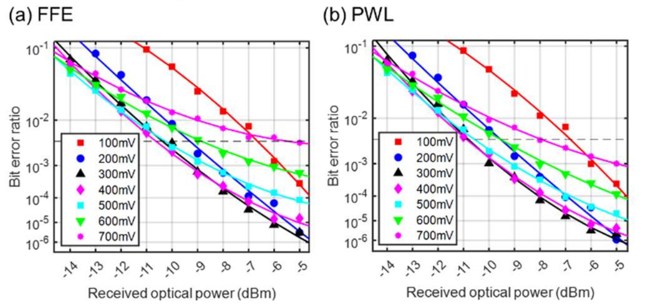

Fig. 5. BER performance of the 56-Gbit/s PAM4 signal using FFE equalizer and PWL after 20-km.

We also compare the computational complexity of the PWL with the FFE and nonlinear equalizer (polynomial nonlinear equalizer, PNLE). Table II summaries the complexity of these equalizers in terms of the number of multipliers. We can observe that the complexity of the proposed equalizer increases linearly with L. In the preceding paragraph, we know that the complexity of PWL equalizer is $N+1$ times of that of standard FFE. In our demonstration, 2 thresholds are sufficient to have acceptable BER performance. Thus, the computational complexity of the PWL equalizer here is three times of that of conventional FFE.

TABLE I. COMPARISON OF COMPLEXITY

	Number of Multipliers
FFE	L
PWL	$(N+1)L$
PNLE3	$L_1+2L_2+3L_3$

Figure 6 shows the BER performance of the 56-Gbit/s PAM4 over 20-km SSMF transmission equalized with FFE, PWL, and 3rd-order PNLE. The swing of driving signal is 600 mV. The FFE has 12 taps while the PWL has 4 taps in each of the 3 parallel linear equalizers to have the same computational complexity. For the 3rd-order PNLE, we set the numbers of taps for the 1st, 2nd, and 3rd orders as 12, 5, and 5, respectively. According to the BER results, the PWL equalizer outperforms FFE equalizer, and achieves a slightly better BER performance than the PNLE3, yet with a 67.57% reduction in the computational complexity.

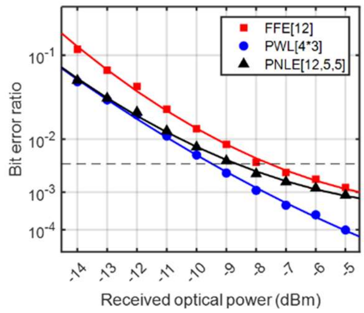

Fig. 6. The BER performance of FFE, PWL, and PNLE with similar complexity.

IV. CONCLUSION

We have experimentally demonstrated that the PWL equalizer can efficiently compensate for non-equally spaced amplitude levels caused by the nonlinear modulation curve of an MZM. The PWL equalizer has only 32.43% of the complexity of a 3rd-order PNLE but has even better performance.

ACKNOWLEDGMENT

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