# Low Power Nonlinear MLSE with Optimized Transition Reservation Mechanism and LUT in Trellis for PAM-4 IM/DD System

Weihao Ni[1], Wei Wang[1], Zhiwei Chen[1], Fan Li[1*] and Zhaohui Li[1,2]
[1] School of Electronics and Information Technology, Guangdong Provincial Key Laboratory of Opto-Electronic Information Processing Chips and Systems, Sun Yat-Sen University, Guangzhou 510275, China
[2] Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519000, China
*lifan39@mail.sysu.edu.cn

*Abstract*—**A low power nonlinear MLSE is proposed, which can compress the transitions in the trellis adaptively. Compared to LUT aided conventional MLSE, up to 90% power consumption can be reduced with neglectable receiver sensitivity penalty.**

***Keywords—maximum likelihood sequence estimation, adjustable threshold detector, look-up table, low power consumption***

## I. Introduction

With the development of cloud service, 4K/8K video, and metaverse over the last years, the traffic intra- and inter-datacenter has increased significantly. Due to the low cost and low complexity of intensity modulation direct detection (IM/DD) [1], [2], the 400 GbE standardization has adopted it and O-band to achieve 100 Gbit/s per channel transmission. To meet the next generation 800 GbE, beyond 800 GbE or 1.6 TbE, the bit rate of per channel will increase to 200 Gbit/s. However, the bandwidth of the CMOS-based transmitter and receiver develops insufficiently [3], which indicates that the bandwidth limitation is an urgent problem to solve. The bandwidth limitation and chromatic dispersion (CD) will induce inter-symbol interference (ISI) that degrades the quality of the received signal and further deteriorates the bit error rate (BER) performance. In addition, nonlinear impairment resulting from the device response and the interaction between CD and direct detection also influences the performance of the system. Maximum likelihood sequence estimation (MLSE) is proven to be the optimal way to alleviate the impact of ISI [4]. However, the power consumption of MLSE increases significantly with the memory length of MLSE, which makes it impractical to apply commercially. Therefore, several studies have been conducted to lower its power cost. For example, a threshold detector is utilized to reduce the number of states in the MLSE trellis [5], or the M method is used to choose active states in the trellis and the MLSE process is only for active states [6]. However, there are some drawbacks to the abovementioned schemes. First, the power dissipation reduction of these schemes is inadequate. Second, the power dissipation reduction for different received optical powers (ROPs) is the same, although the power consumption is supposed to be reduced more with a higher ROP. For the nonlinear issue, one popular solution is using the Volterra equalizer or deep neural network (DNN) equalizer to combine with the MLSE scheme [7], [8]. Another widespread solution is adopting a look-up table (LUT) to replace the dot product calculation in the branch metric construction [9]. In this paper, we propose a low power nonlinear MLSE scheme which is called optimized transition reservation mechanism and LUT aided MLSE (OTRM-LUT-MLSE). This scheme overcomes all the abovementioned drawbacks. It can compress the number of transitions adaptively in the trellis depending on the quality of equalized symbols. In addition, this scheme is demonstrated in 60 GBaud and 70 GBaud PAM-4 signal transmissions with 2.4 GHz -3dB bandwidth, and up to 90% power consumption can be decreased with negligible receiver sensitivity penalty, which is a significant reduction.

## II. 2. Optimized Transition Reservation Mechanism and LUT Aided MLSE

Figure 1(a) shows the block diagram of the proposed OTRM-LUT-MLSE. The main structure of this method consists of three adaptive filters, a LUT generation unit, an adjustable threshold detector, and an OTRM-LUT-MLSE unit. The first filter is a feed-forward equalizer which is utilized to eliminate the ISI of the current instant signal and shorten the channel response to reduce the necessary memory length in MLSE. However, FFE will cause noise enhancement of high frequency. The second filter is a low pass filter (LPF) which is used to suppress the enhanced high-frequency noise. The third filter, called desired impulse response (DIR), is capable of simulating the frequency response which is not influenced by gaussian noise. The LPF and DIR take advantage of the same error to converge, thus the LPF can filter out the abovementioned noise effectively and retain the original signal at the same time. The adjustable threshold detector is used for pre-decision to obtain pre-information that can assist in the power consumption reduction of MLSE. Its mechanisms are shown in Fig. 1(b). The adjustable threshold detector can minimize the possible level range and decrease the transitions adaptively for every transmitted symbol. To minimize the probable level range can reduce the number of states in the trellis effectively, for example, 16 states at every instant can be decreased to 4 states when the memory length of MLSE is 3. It is worth noting that states of the current instant in the trellis are combinations of pre_info at the current instant and the previous instant. Especially, the output of the adjustable threshold detector may contain 0 element, which can be regarded as an inactive element. And there will be no transition to or from states that include 0 element. That is the reason for the compression of transitions. The parameter $W$ can be utilized to adjust the frequency of the 0 element. The larger $W$ is, the 0 element will occur in the pre_info at more instants. There are 8 possible trellis diagram cases based on different combinations of pre_info, as shown in Fig. 1(c). Afterward, the outputs of LPF, and adjustable threshold detector together

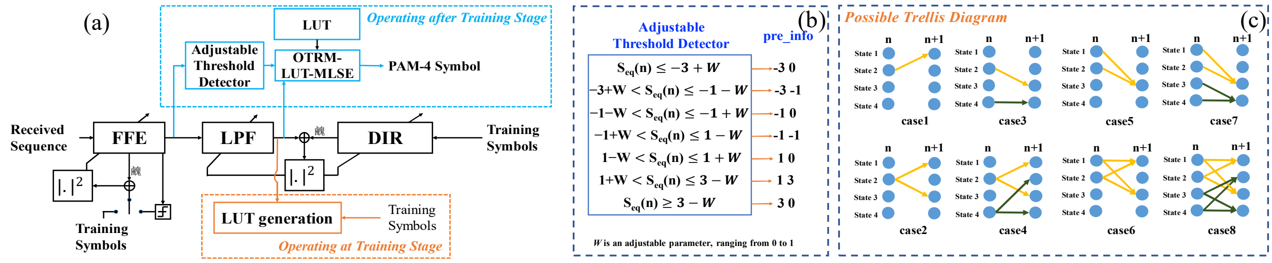


Fig. 1. (a) Block diagram of OTRM-LUT-MLSE scheme. (b) The mechanism of adjustable threshold detector. (c) All possible trellis diagrams of OTRM-LUT-MLSE.

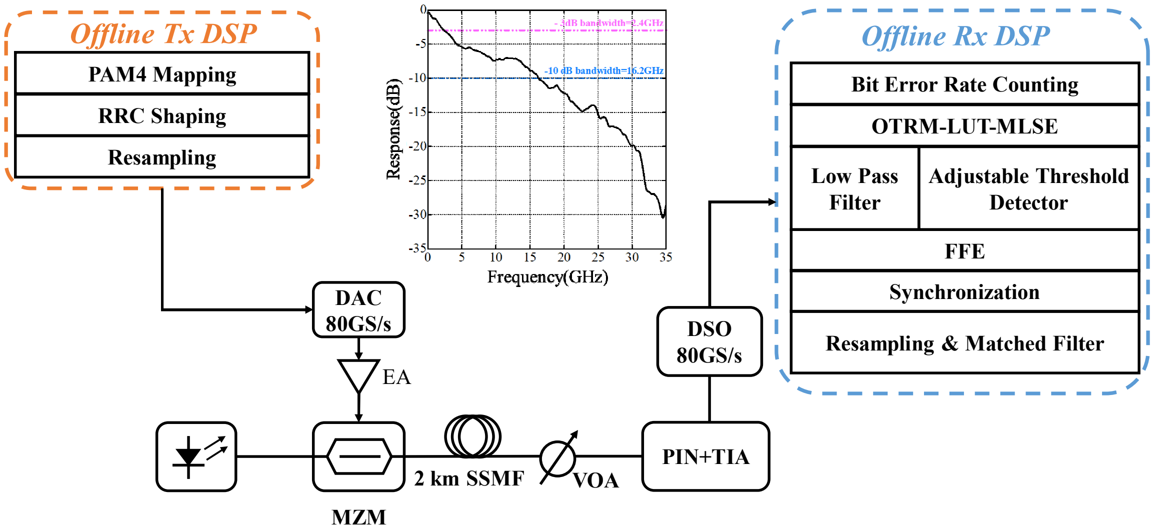


Fig. 2. Experimental Setup and frequency responses of the transmission system

with generated LUT will be fed into OTRM-LUT-MLSE to recover the transmitted PAM-4 symbols.

## III. Experimental Setup and Results

The performance of the proposed OTRM-LUT-MLSE has been experimentally evaluated in 65 GBaud and 70 GBaud PAM-4 signal transmission systems. Fig. 2 shows the experiment setup. The transmission data sequence of the PAM-4 signal is generated by offline DSP and a 16 GHz, 80 GSa/s digital-analog converter (DAC). The amplified signal and 1550 nm optical signal are both fed into the Mach-Zehnder modulator (MZM) to achieve electrical-to-optical (E/O) conversion. The optical signal is transmitted through 2 km standard single-mode fiber (SSMF). And the received optical power is adjusted by a variable optical attenuator (VOA). After that, a PIN photodiode integrated with a trans-impedance amplifier (TIA) is adopted to accomplish the optical-to-electrical (O/E) conversion. The converted signal is captured by a 36 GHz, 80 GSa/s Digital Storage Oscilloscope (DSO), which realizes the analog-digital conversion. The digital sequence is processed by the offline DSPs to recover the transmitted PAM-4 symbols. Fig. 2 also shows the frequency response of the transmission system. The -3 dB and -10 dB bandwidths of our system are 2.4 GHz and 16.2 GHz, respectively.

The occurrence probability of different compressed trellis cases with different *W* has been statistically analyzed as shown in Fig. 3. The probability of cases with fewer transitions gradually increases along with the growth of W, which means the power consumption can be reduced more. After that, the BER performance of conventional MLSE, LUT aided conventional MLSE, and OTRM-LUT-MLSE with different values of parameter *W* in different transmitted conditions has been compared as shown in Fig.4(a)-(c). The corresponding power dissipation reduction at different ROPs is shown in Fig.4(d)-(f). In 60 GBaud PAM-4 signal BTB transmission, the BER performance of OTRM-LUT-MLSE with different *W* is all nearly consistent with LUT aided conventional MLSE. In 65 GBaud 2 km SSMF transmission, the deterioration of BER performance is observed with the increase of *W* when the OTRM-LUT-MLSE is utilized. However, the performance of the proposed scheme is still superior compared with conventional MLSE. Especially, the proposed scheme still can maintain ~0.95dB receiver sensitivity gain, even though *W* is set as 0.3. And the ROP penalty of OTRM-LUT-MLSE is controllable by adjusting the value of parameter *W*. The results of 70 GBaud BTB transmission are similar to 65 GBaud 2 km SSMF transmission. The BER of conventional MLSE is above the 7% HD-FEC threshold at this condition. However, the proposed OTRM-LUT-MLSE is still capable of reaching the 7% HD-FEC threshold when the W=0, 0.1, and 0.2, which proves that the robustness of this low power nonlinear MLSE scheme is remarkable. Comparing the power consumption reduction in Fig. 4(d)-(f), ~90% power consumption can be reduced for all transmissions at least and a slight decline can be observed with the growth of the baud rate. It is worth noting that more power consumption reduction can be realized with higher ROP, i.e., signal noise ratio (SNR), which proves the proposed OTRM-LUT-MLSE can decrease the power cost of MLSE dynamically depending on the SNR

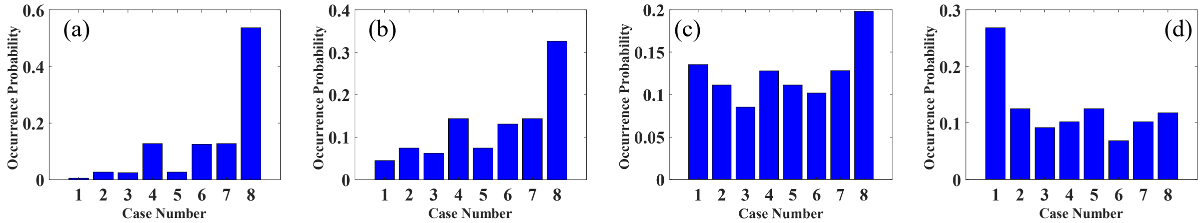


Fig. 3. The occurrence probability of different trellis cases when (a) $W$=0, (b) $W$=0.1, (c) $W$=0.2, (d) $W$=0.3 (65 GBaud PAM-4 signal BTB transmission with -8 dBm ROP).

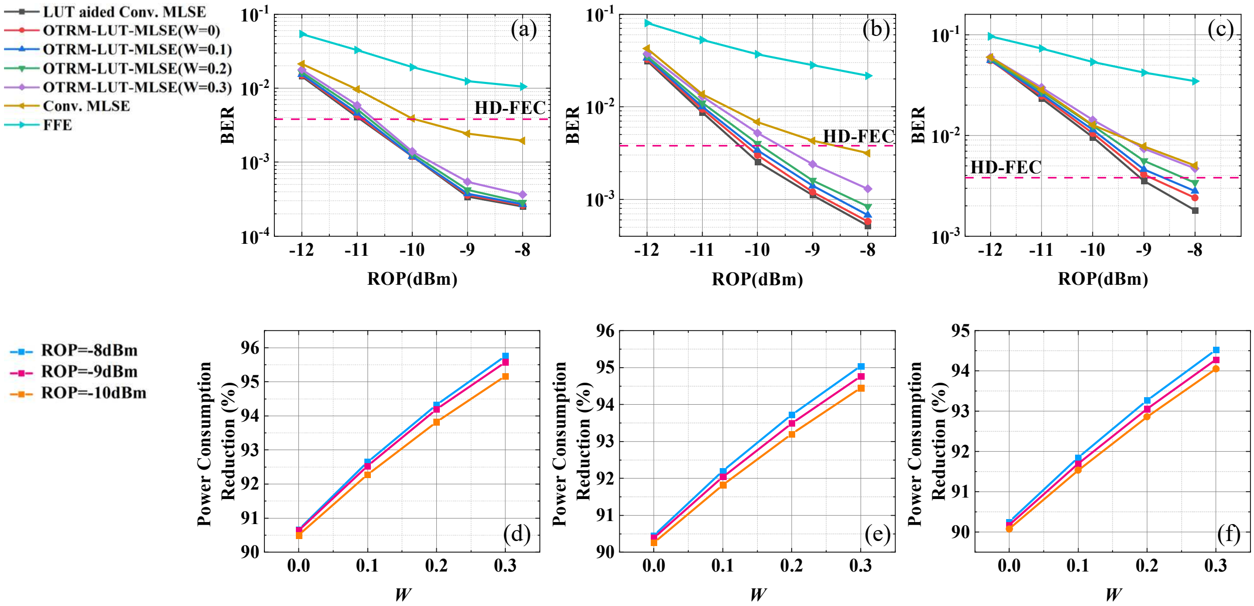


Fig. 4. The BER performance comparison and corresponding power consumption reduction (%) with different $W$ in 65GBaud PAM-4 BTB (a) and (d), 65GBaud PAM-4 2km SSMF (b) and (e), and 70GBaud PAM-4 BTB transmission (c) and (f).

of the signal. And the adjustability of power consumption reduction can be observed by increasing the $W$.

## IV. Conclusion

A low power consumption nonlinear MLSE scheme called OTRM-LUT-MLSE is proposed, in which the transitions in the trellis can be adaptively compressed based on the quality of equalized symbols. This scheme can achieve effective ISI and nonlinear impairment elimination like LUT aided conventional MLSE at an extremely low power cost. Experimental results prove that it achieves ~90% power consumption reduction with neglectable ROP penalty when 65 GBaud and 70 GBaud PAM-4 signal is transmitted with 2.4 GHz -3 dB bandwidth.

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