Computationally Efficient 120 Gb/s/λ PWL Equalized 2D-TCM-PAM8 in Dispersion Unmanaged DML-DD System

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Abstract: We proposed a PWL equalizer in 120 Gb/s 2D-TCM-PAM8 based DML-DD system to correct eye skew. Computationally efficient 120 Gb/s 8-state 2D-TCM-PAM8 over 2 km C-band transmission is demonstrated below HD-FEC (3.8×10^{-3}).

1. Introduction

Pulse-amplitude-modulation (PAM) based directly-modulated laser-direct detection (DML-DD) system has been studied extensively for short reach optical communications due to its low complexity and low cost. Many specialized techniques are proposed to squeeze more data in a given bandwidth to cope with dispersion-induced power fading, such as Thomlinson-Harashima precoding (THP) [1, 2], PAM4-duobinary [3-5] and PAM6, 7, 8 [6-8]. Recently, a two-dimensional PAM8 scheme with trellis-coded modulation (2D-TCM-PAM8) has been proposed for a high coding gain with high spectral efficiency [9]. However, there are some challenges to directly apply this technique in high bitrate (>100 Gb/s) DML-DD systems in the C band. The main obstacle is the interaction between the adiabatic chirp of the DML and fiber chromatic dispersion. First, it leads to a signal-level dependent skew, which degrades the signal quality. Second, the fiber channel can no longer be treated as an additive white Gaussian noise (AWGN) channel, thereby decreasing the coding gain from the trellis codes [10].

In this paper, we propose to use a piecewise linear equalizer (PWL) [11, 12] prior to Viterbi decoding to rectify the channel response to an AWGN channel. Therefore, the coding gain of the trellis codes can be preserved. By using the PWL equalizer and 8-state Viterbi decoder, we demonstrate a 120 Gb/s 2D-TCM-PAM8 transmission over 2 km in the C band for the DML-DD system. Bit error rate (BER) performance under the hard-decision forward error correction (HD-FEC) threshold of 3.8×10-3 is achieved. Compared with the works utilizing Volterra equalizer and 16-state maximum likelihood sequence estimation (MLSE) equalizer [3, 4], this scheme features a much lower computational complexity.

2. Principle

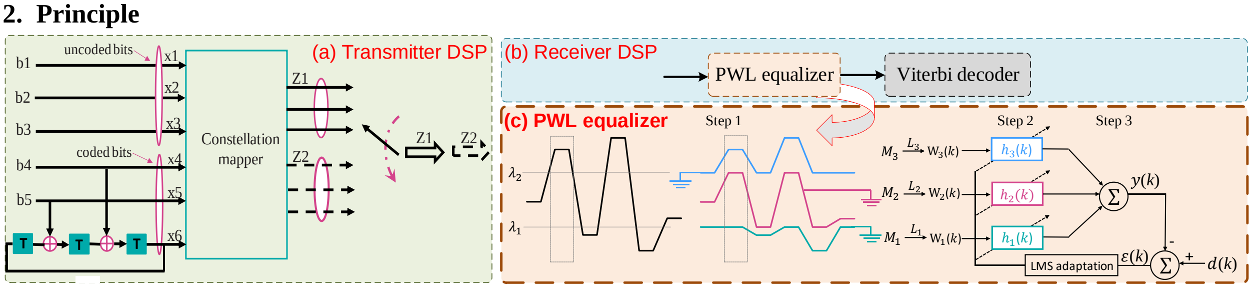

Fig. 1. (a) Configuration of transmitter DSP: generation process of 2D-TCM-PAM8 signal, (b) Receiver DSP consists of PWL equalizer and Viterbi decoder, and (c) Procedures for PWL equalizer.

The transmitter-side digital signal processing (DSP) for the 2D-TCM-PAM8 signal is shown in Fig. 1(a), which consists of a convolutional encoder and a constellation mapper. After an 8-state convolutional encoder, 3 uncoded bits (x1-x3) and 3 coded bits (x4-x6) are obtained. Then the digital signals will be mapped to two consecutive PAM8 symbols, Z1 and Z2, in the time domain after the constellation mapper. Since two symbols are generated from 5 information bits, the 2D-TCM-PAM8 signal features 2.5 bits per symbol.

The receiver-side DSP includes the PWL equalizer [11] and Viterbi decoder (Fig. 1(b)). The PWL equalizer consists of three processing steps, including amplitude threshold decomposition, linear multichannel equalization, and linear addition (Fig. 1(c)). More details can be found in [11]. To elaborate threshold decomposition clearly, we take the second received sample $r = 5.3$ in sequence $\mathbf{X} = [-1, 5.3, -5, 6.7, -6.9, -3]$ (see Fig. 1(c)) as an example,

1) Define thresholds set: $\tau = \{-4, 2.5\}$, that is $\lambda_1 = -4$ and $\lambda_2 = 2.5$.

2) Obtain 3 disjoint intervals partitioned by τ: $I_1 = (-\infty, -4)$, $I_2 = [-4, 2.5)$, and $I_3 = [2.5, \infty)$.
3) Since $\gamma = \mathbf{x}(2) = 5.3 \geq 0$, $\gamma \in I_3$, and $\lambda_2 > 0$, we can obtain $M_3(2) = 5.3 - 2.5 = 2.8$. Similarly, $M_1(2) = 0$ and $M_2(2) = 2.5$ can be got.

After threshold decomposition, the received signal is decomposed to $N+1$ segments $M_1, M_2, M_3 \ldots M_{N+1}$ using a threshold set $\tau = \{\lambda_1, \lambda_2 \ldots \lambda_N\}$. The PWL equalizer consists of $N+1$ linear equalizers (e.g., FFE) in parallel for the $N+1$ decomposed segments. Given the present sample for M_i is $M_i(k)$, $\mathbf{W}_i(k)$ is given in Eq. (1), $i = 1, 2 \ldots, N+1$.

$$\mathbf{W}_i(k) = \begin{bmatrix} M_i(k) \\ M_i(k-1) \\ \ldots \\ M_i(k-L_i+1) \end{bmatrix}, \mathbf{H}_i(k) = \begin{bmatrix} h_{i1}(k) \\ h_{i2}(k) \\ \ldots \\ h_{iL_i}(k) \end{bmatrix} \tag{1}$$

The corresponding weights of the equalizers are given by $\mathbf{H}_i(k)$ with a fixed length of L_i taps. Finally, we sum the outputs from the $N+1$ parallel equalizers. In other words, the output $y(k)$ of the PWL equalizer is an inner product of $\mathbf{W}_i(k)$ and the transposed vector of $\mathbf{H}_i(k)$. $\mathbf{H}_i(k)$ is updated using least mean square (LMS) algorithm.

3. Experimental setups

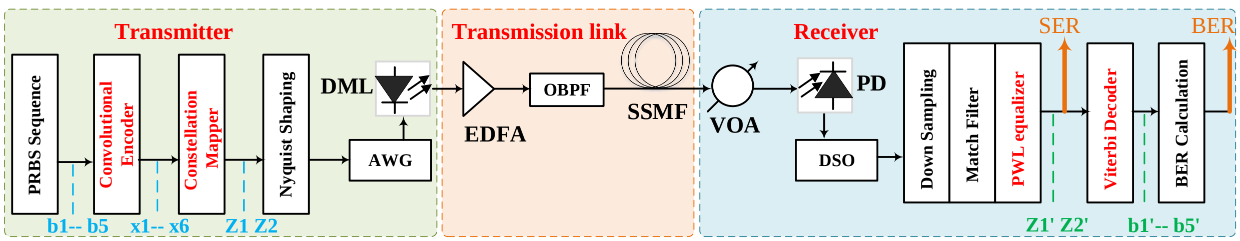

Fig. 2 Experimental setups of 2D-TCM-PAM8 signal in DML-DD transmission.

Fig. 2 shows the experimental setups. At the transmitter, the 120 Gb/s (48 GBd) 2D-TCM-PAM8 signal is generated with preprocessed data from the convolutional encoder, constellation mapping and root-raised cosine filter with a roll-off factor of 0.01. Then, the output signal of AWG (65 GSa/s) with peak-to-peak voltage (Vpp) of 0.95 V sequentially passes through a 6-dB radio frequency (RF) attenuator, an RF amplifier with 26 dB gain (SHF806A) and another 6-dB RF attenuator before launching into the DML. The DML's center wavelength, 3-dB bandwidth, bias current, and output power are 1550.9 nm, ~20 GHz, 115 mA, and 7.5 dBm, respectively. The high bias current of the DML leads to adiabatic chirp dominated behavior. The launched power into the 2 km SSMF is 11 dBm. After transmission, a variable optical attenuator (VOA) is used to adjust the received optical power (ROP) for performance evaluation. The signal is finally launched into a photodiode (PD) with 70 GHz bandwidth. A digital storage oscilloscope (DSO) with 80 GSa/s sampling rate and 32 GHz bandwidth records the detected signal. The signal samples are sent into a digital match filter with a roll-off factor of 0.01, and downsampled to two samples per symbol. Then the digital signal is equalized by the PWL equalizer. In this experiment, we choose threshold partitioning $\tau = \{\lambda_1, \lambda_2\}$ to test the performance of the 2D-TCM-PAM8 signal. After the PWL equalizer, an 8-state Viterbi decoder is used to decode the trellis of 2D-TCM-PAM8 signal with shallow memory. A total number of 32768 symbols are used to evaluate the bit error ratio (BER) performance of 2D-TCM-PAM8.

4. Experimental results

For the PWL equalized 2D-TCM-PAM8, we first optimized the threshold sets $\tau = \{\lambda_1, \lambda_2\}$ of the PWL to achieve the best performance. Before three parallel FFEs, we used a pre-equalizer (an 11-tap FFE) to distribute signal around $[-7, -5, -3, -1, 1, 3, 5, 7]$ to facilitate accurate segmentation; thus, most of the pre-equalized signals are within the range of $[-8, 8]$. So, both λ_1 and λ_2 are varied from -8 to 8 to find the optimum threshold set for the case of 120 Gb/s after 2 km transmission with a fixed ROP of 7.6 dBm. A contour diagram of SER performance versus threshold sets λ_1 and λ_2 of the PWL equalizer is shown in Fig. 3(a). The worst SERs occur at the threshold sets of $\{-8, -8\}$, $\{-8, 8\}$ and $\{8, 8\}$ because the PWL equalizer works as conventional FFE equalizers in such scenarios. A skewed eye diagram with the threshold set $\{8,8\}$ can be seen in Fig. 3(i). Thanks to the PWL equalizer, the skewed eyes can be rectified using the PWL equalizer with a threshold set of $\{-5,6\}$ (see Fig. 3(ii)). We then use the threshold set $\{-5,6\}$ and 181-tap for each segment in PWL for the following analysis.

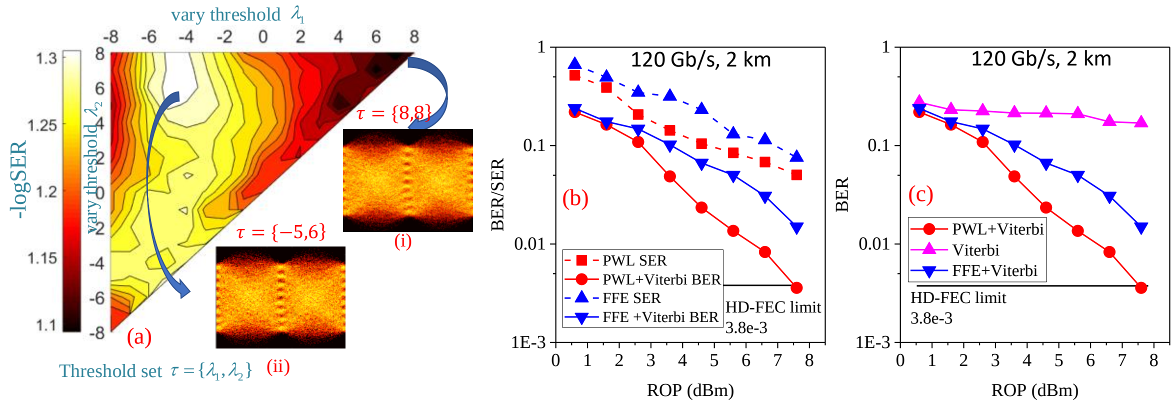

Fig. 3 (a) Contour diagram of -log(SER) performance versus threshold sets λ_1 and λ_2 of PWL equalizer, (i) and (ii) corresponds to eye diagrams in 120 Gb/s over 2 km transmission @ROP= 7.6 dBm for PWL equalizer with threshold sets: $\{8,8\}$ and $\{-5,6\}$, respectively. (b) the comparisons between PWL and FFE without Viterbi decoder, and with Viterbi decoder, and (c) the comparisons between with PWL, without equalizer and with FFE in 120 Gb/s over 2 km transmission, respectively.

We compared the performance of PWL and FFE in Fig. 3(b). Here FFE has the same tap of each segment of PWL equalizer. The SER of PWL is slightly better than that of FFE due to a slight eye skew after 2 km transmission, which can only be corrected by PWL, instead of FFE. When the 8-state Viterbi decoder is used following the equalizers, PWL with Viterbi shows huge superiority to FFE with Viterbi since Viterbi is a sequential decoding algorithm that is sensitive to slightly better SER. In Fig. 3(c), 2D-TCM-PAM8 without any equalizers before Viterbi decoder, i.e., with only Viterbi decoder, delivers quite poor BER performance. It is because TCM only works in the AWGN channel, and the adiabatic chirp distorted channel and bandwidth-limited channel are not AWGN channel. Once Viterbi decoder is used following the PWL, the BER improves a lot compared with no equalizer case. Since 2D-TCM-PAM8 with FFE only compensates the linear distortion, it performs better than no equalizer case but is inferior to 2D-TCM-PAM8 with PWL. Therefore, only the case of PWL and Viterbi decoder can support 120 Gb/s over 2 km transmission below the HD-FEC limit (3.8×10^{-3}).

Before the TCM scheme, Volterra and MLSE with at least 2-memory (16-state for PAM4) are usually used in the bandwidth-limited system to compensate the nonlinear distortions [3, 4]. We have confirmed that PWL equalizer can achieve a similar BER performance with 2nd order Volterra equalizer yet with lower complexity in [12]. As for MLSE, its implementation complexity can be very high when the searching state size is large. Only 8-state Viterbi decoder is used in this work, instead of 16-state decoder. Therefore, this work features a much lower computational complexity.

5. Conclusions

We, for the first time, proposed PWL equalizer and applied it prior to the Viterbi decoder. Therefore PWL equalizer can compensate for the skewed eye diagram and enable 2D-TCM-PAM8 to keep its coding gain. By using PWL equalizer and 8-state Viterbi decoder, we have demonstrated 120 Gb/s 2D-TCM-PAM8 with 8 state encoder over 2 km transmission in the C band below HD-FEC with low complexity.

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