Experimental Demonstration of C-band 112-Gb/s PAM4 over 20-km SSMF with Joint Pre- and Post-equalization

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Abstract: We demonstrate C-band 112-Gb/s PAM4 over 20-km transmission with pre- and post-equalization. Pre-filter coarsely pre-compensates system bandwidth at transmitter while FFE-DFE with erasure technology jointly post-compensates residual bandwidth limitation and dispersion-induced power fading at receiver. © 2020 The Author(s)

1. Introduction

In order to support high-bandwidth demanding services, like virtual and augmented reality (VR/AR), cloud computing and 5G mobile transport, the telecom industry is seeking higher capacity solution for the short-reach transmission application scenarios, such as mobile fronthaul and data center optical interconnect [1]. Intensity modulation and direct detection (IM/DD) systems feature small form factors, low cost and low power consumption, which are preferred for short-reach transmission compared to coherent systems. Besides, four-level pulse amplitude modulation (PAM4) is a promising format for IM/DD systems, which has also been elected as a standard format for 400-G Ethernet [2].

The main challenges for high-speed PAM4 systems are limited system bandwidth and power fading caused by chromatic dispersion (CD) and direct detection [3]. On the one hand, electrical equalizations based on digital signal processing (DSP) have been proposed to eliminate inter symbol interference (ISI) caused by bandwidth limitation. But on the other hand, the main obstacle for PAM4 systems is CD of fiber, which gives rise to severe power fading caused by CD and square-law detection. In a recent report [4], it showed that C-band 112-Gb/s PAM4 transmission distances are generally limited to below 10 km. Extensive modification works such as Kramers-Kronig receiver, CD pre-compensation and single sideband or vestigial sideband (SSB/VSB) modulation have been proposed to cope with CD [5]. However, these methods require complex system architecture and additional expensive devices, which are not cost-effective solutions for short-reach transmission systems. Therefore, if we maintain the traditional structure of IM/DD systems, it is worthwhile to investigate advanced DSP algorithms to further increase CD tolerance.

In this work, we firstly propose to adopt joint pre- and post-equalization to compensate bandwidth limitation and dispersion-induced power fading for PAM4 systems. In order to release the requirement of accurate channel estimation and channel feedback, the proposed pre-equalization is based on a simple 2-tap finite impulse response (FIR) filter, which coarsely pre-compensates bandwidth limitation at transmitter and is of low computational complexity as well. At receiver, post-equalization based on modified feed-forward equalizer and decision feedback equalizer (FFE-DFE) is applied to flexibly compensate residual bandwidth limitation and dispersion-induced power fading. Moreover, error erasure technology is introduced in the decision process to mitigate error propagation. By combining joint pre- and post-equalization DSP techniques, experimental results show that the bit error ratio (BER) reaches 2.9×10^{-3} at a received optical power (ROP) of 0 dBm, which is below 7% feedforward error correction (FEC) threshold. To the best of our knowledge, we achieved the first C-band 112-Gb/s PAM4 system over 20-km SSMF transmission through only applying advanced DSP algorithms.

2. Experimental setup and DSP

Fig. 1 shows the experimental setup of C-band 112-Gb/s PAM4 system. At transmitter, the offline generated electrical signal by arbitrary waveform generator (AWG) was appropriately adjusted by a 19-dB driver and a 6-dB attenuator. A laser with central wavelength of 1550.12 nm was employed to generate optical carrier. A Mach-Zehnder modulator (MZM) was used to modulate the electrical signal into optical domain. The launch power into fiber was +4 dBm. At receiver, a variable optical attenuator (VOA) was applied to adjust received optical power and a PIN-photodetector (PD) was employed to achieve photoelectric conversion. Finally, the electrical signal was captured by a real-time oscilloscope (RTO). The system frequency response at optical back to back (OBTB) transmission is also shown in Fig. 1(a). The whole system is of around -3dB bandwidth of 5 GHz and -10dB bandwidth of 21 GHz.

Fig. 1(a) shows the DSP flow at transmitter and receiver, respectively. At the transmitter side, each 72400 bits are mapped to one PAM4 frame with Gray code. Noted that the first 1000 PAM4 symbols are considered as training sequence for the receiver-side equalization. Afterwards, the PAM4 signal is up-sampled with factor of 2. Then, a square root-raise-cosine filter with factor of 0.4 is applied to do pulse shaping. Next, a 2-tap FIR pre-filter is employed to do channel pre-equalization. The Z-domain expression of 2-tap FIR pre-filter can be written as

$$H_{pre-filter} = 1 + \alpha Z^{-1} \quad (1)$$

The normalized frequency response of pre-equalization with different α is depicted in Fig. 1(b). The pre-filter would enhance high-frequency response while decrease low-frequency response. The variation degree of frequency response varies according to the α. In addition, pre-equalization with different α would also cause a growth in signal peak to average power ratio (PAPR), which can be seen in Fig. 1(c). When α goes from 0 to -1, the PAPR increases from 6 dB to approximate 10 dB. The adopted 2-tap FIR pre-filter has the following two advantages compared to pre-equalization with the inverse of channel response: 1) The 2-tap FIR pre-filter doesn't require accurate channel estimation and channel feedback; 2) The computational complexity of pre-equalization is extremely low since only 2-tap FIR filter is applied.

At the receiver side, a modified FFE-DFE with erasure technology is proposed for mitigating residual bandwidth limitation and dispersion-induced power fading. However, a big issue for FFE-DFE is that when the output samples are close to the decision threshold, the corresponding decision symbols would be unreliable. In other words, uncertain decisions are likely to give rise to incorrect feedback symbols, thus resulting in error propagation. Therefore, a novel decision criterion with erasure technology for PAM4 signal in modified FFE-DFE is proposed, which can be seen in Fig. 1(d). The difference is that modified FFE-DFE adopts novel decision criterion that introduces intermediate decision symbols for unreliable decision region. Here, (-2-γ_1, -2+γ_1), (-γ_2, +γ_2) and (2-γ_1, 2+γ_1) are the unreliable decision region, which are sentenced to -2, 0, and +2, respectively. The γ_1 and γ_2 are erasure factors. Noted that continuous update for tap coefficients is applied to all of the equalizers.

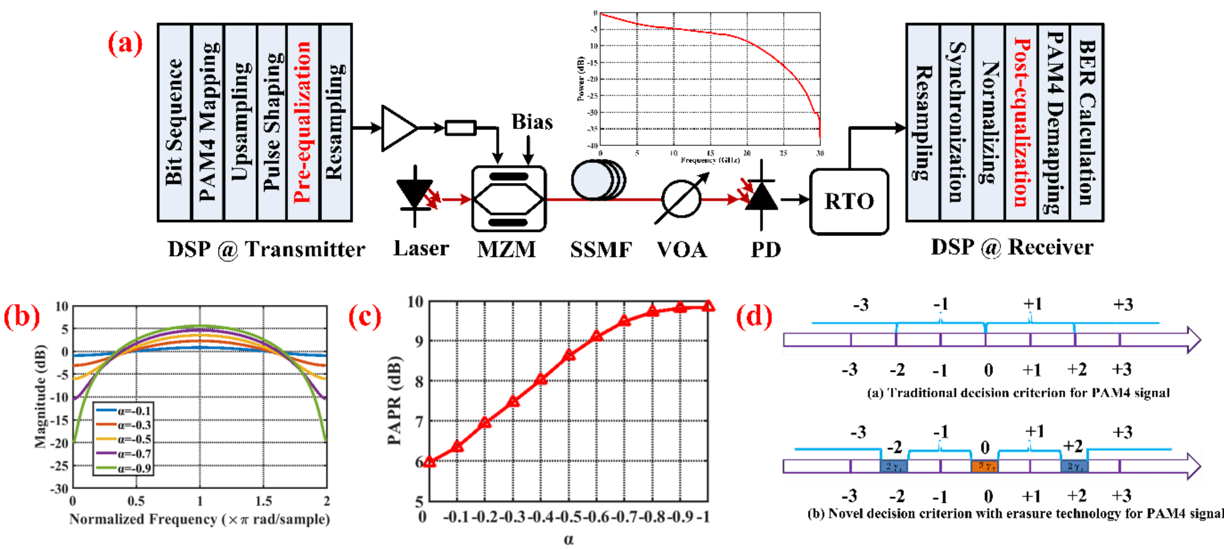

Fig. 1 (a) Experimental setup of C-band 112-Gb/s PAM4 system; (b) Frequency response of pre-filter with different α; (c) Signal PAPR after pre-filter with different α; (d) Traditional and novel decision criterion for PAM4 in modified FFE-DFE.

3. Experimental results and discussion

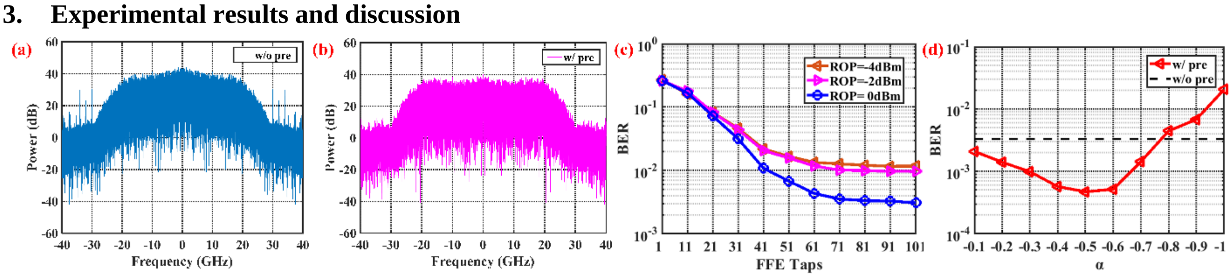

Fig. 2 (a) Received signal spectrum without pre-equation; (b) Received signal spectrum with pre-equalization; (c) BER versus FFE taps for OBTB transmission without pre-equalization; (d) BER versus α for pre-equalization at received optical power (ROP) of 0 dBm.

Fig. 2 shows transmission performance for OBTB transmission. Fig. 2(a) and Fig. 2(b) depict the received signal frequency spectrums without and with pre-equalization, respectively. The signal frequency spectrum with pre-equalization is flatter than that without pre-equalization. In order to compensate the insufficient system bandwidth, FFE with optimized 81 taps are investigated to compensate limited bandwidth, which can be found in Fig. 2(c). However, FFE would increase noise as well when system bandwidth is compensated, which enables the achieved BER with FFE is limited to 3.3×10^{-3} at ROP of 0 dBm. Fig. 2(d) shows the BER performance versus different α for pre-equalization. It depicts that pre-equalization with α ranging from -0.1 to -0.7 achieves better BER compared to that without pre-equalization. The optimal BER performance is achieved at α=-0.5 with a BER of 5.5×10^{-4}. Therefore, pre-equalization is good for achieving better transmission performance.

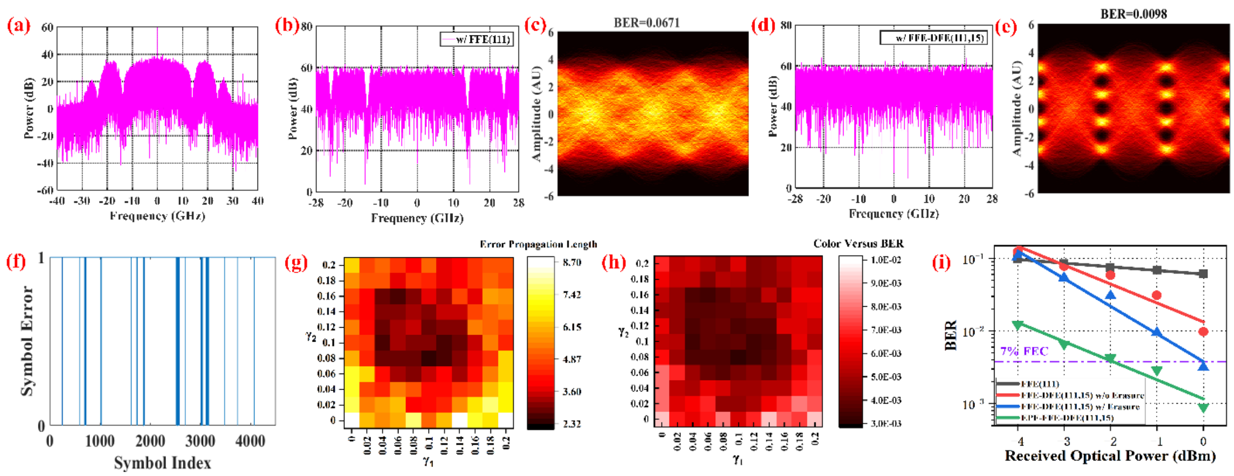

Fig. 3 (a) Received signal spectrum after 20-km transmission; (b-e) Recovered signal spectrums and eye diagrams with FFE and FFE-DFE, respectively; (f) Symbol error with FFE-DFE; (g-h) Error propagation length and BER with different erasure factors; (i) BER versus ROP with different equalizations.

Fig. 3 shows transmission performance for 20-km SSMF transmission. Fig. 3(a) shows received frequency spectrum after 20-km SSMF transmission, which obviously suffers from severe power fading. Fig. 3(b-e) depict recovered signal spectrums and eye diagrams with FFE and FFE-DFE, respectively. Fig. 3(b) shows deep nulls since FFE cannot equalize them. Also, the recovered eye diagram with FFE in Fig. 3(c) is quite obscure. Fortunately, FFE-DFE can compensate spectrum nulls by inserting poles [6]. Hence, Fig. 3(d) shows that the recovered signal spectrum with FFE-DFE shows no spectrum nulls. Moreover, Fig. 3(e) depicts a clear recovered eye diagram with FFE-DFE. However, the BER only reaches 9.8×10^{-3}. In order to find the reason for that bad BER, Fig. 3(f) depicts lots of successive symbol errors, namely error propagation. Therefore, erasure technology with different erasure factors is employed to mitigate error propagation. Here, the average error propagation length is defined as $\frac{SER_{EP}}{SER_{EPF}}-1$, in which SER_{EP} represents symbol error ratio (SER) with FFE-DFE and SER_{EPF} denotes SER with error-propagation-free FFE-DFE (EPF-FFE-DFE). Noted that EPF-FFE-DFE is achieved by using all of the sending data as training sequence. Fig. 3(g-h) shows the average error propagation length decreases from 8.7 to 2.3 and the BER also reduces from 9.8×10^{-3} to 2.9×10^{-3} when γ_1=0.1 and γ_2=0.08, which verifies the feasibility of erasure technology. Fig. 3(i) shows BER versus ROP with different equalizations. The FFE-DFE with erasure technology achieves a BER of 2.9×10^{-3} at a ROP of 0 dBm. In addition, the traditional FFE and FFE-DFE can hardly achieve 7% FEC threshold. Although the EPF-FFE-DFE achieves the best performance, real implementation cannot adopt all sending data as training sequence.

4. Conclusion

Owing to the effectiveness of joint pre- and post-equalization DSP techniques, we successfully demonstrated the first C-band 112-Gb/s PAM4 signal over 20-km SSMF transmission. We believe that the proposed equalization scheme has made significant impacts in short-reach, low-cost transmission applications.

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