112-Gb/s/λ Downstream Transmission for TDM-PON with 31-dB Power Budget using 25-Gb/s Optics and Simple DSP in ONU

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Abstract: We experimentally demonstrate 112-Gb/s/λ PAM-4 transmission based on 25-Gb/s optics. Over 31-dB power budget is achieved by using OLT-side pre-equalization, amplification and only simple FFE in ONU.

OCIS codes: (060.2330) Fiber optics communications, (060.4080) Modulation.

1. Introduction

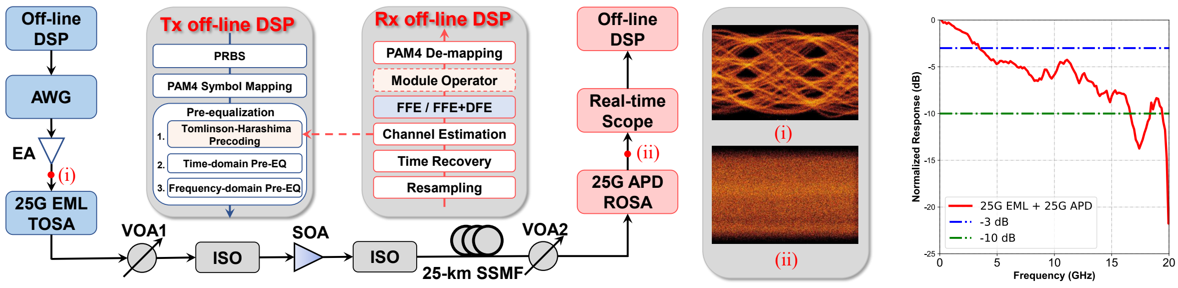
The continuous growth of emerging technologies such as real-time online games, cloud services and Big Data have resulted in the demand of high-speed optical access networks. IEEE 802.3ca Working Group proposes a total capacity of 100-Gb/s for next generation Ethernet passive optical network (NG-EPON) [1]. And the channel rate per wavelength of 100-Gb/s and even beyond have been widely studied recently for 400 Gigabit Ethernet.

To realize TDM-PON with higher single wavelength speed, advanced modulation formats and equalization techniques are of great value using cost-effective off-the-shelf optical devices. Four-level pulse-amplitude modulation (PAM-4) is a good candidate in consideration of its simplicity and effectiveness. However, high-order modulation formats increase data rate with the cost of inferior receiver sensitivity. Therefore, pre- and post-equalization techniques can be combined to improve the BER performance of the system. Pre-equalization (Pre-EQ) techniques including finite impulse response (FIR) filtering, frequency domain equalization, look-up table (LUT) and Tomlinson-Harashima precoding (THP) have been extensively used to eliminate inter-symbol interference (ISI) in PAM signal intensity modulation and direct detection (IM/DD) transmission system [2–4]. And the remaining ISI can be compensated by feed-forward equalization (FFE) [5, 6], which can minimize the digital signal processing (DSP) complexity at the optical network unit (ONU) side in the downstream link. However, it remains difficult to support the PR-30 link loss budget.

In this paper, we report a PAM-4 IM/DD PON system at the rate of 112-Gb/s/λ based on commercial 25-Gb/s optics in the O-band. We compare the effects of several pre- and post-equalization techniques on sensitivity improvement. Experimental results show that by using THP-based centralized DSP in OLT, the equalizer required at the receiver side can be significantly simplified, and a sensitivity of -20.1 dBm at the LDPC limit is obtained. Furthermore, by using an SOA at the OLT side for power boosting, the link power budget of 31.58-dB is achieved.

2. Experimental Setup

The experimental setup for 112-Gb/s PAM-4 TDM-PON downstream transmission system is depicted in Fig. 1(a). At the OLT side, the 112-Gb/s PAM-4 signal with Pre-EQ is generated in Matlab and then uploaded into an arbitrary waveform generator (AWG) with 88 GSa/s maximal sample rate. The amplitude of the signal generated by the AWG is 210 mV. After that, the PAM-4 signal is amplified to a peak-to-peak voltage of 2V through a 55-GHz electrical amplifier, and then drives the 25-Gb/s electro-absorption modulated laser based TOSA (25G EML TOSA) operating at 1304.89 nm. The output power of the EML is roughly 1.9-dBm. An SOA booster is used to increase the launch power prior to 25-km standard single mode fiber (SSMF) transmission, which has small-signal gain of 14.4-dB and noise figure of 5.9-dB, simultaneously offers saturation output power of 11.7-dBm. Two optical isolators are placed before and behind the SOA to avoid unwanted optical reflections. To explore the impact of the power injected into the SOA on the bit error rate (BER) performance, we add a variable optical attenuator (VOA) to vary the input power of SOA. At the ONU side, another VOA is inserted in front of the receiver to adjust the received optical power (ROP) for sensitivity measurement. Then a 25-Gb/s avalanche photodiode (APD) based receiver optical sub-assembly (ROSA) is used for optical-to-electrical conversion. The output of APD is digitized at 80-GSa/s by a 33-GHz real-time digital storage oscilloscope (DSO) and then processed off-line in Matlab. The 10-dB bandwidth of the whole system is roughly 17-GHz as indicated in Fig. 1(b), which will cause strong ISI penalty. The electrical eye diagrams of the PAM-4 signal before EML and received by ADP at -16 dBm ROP for downstream link as the insets (i) and (ii) of Fig. 1(a) show.



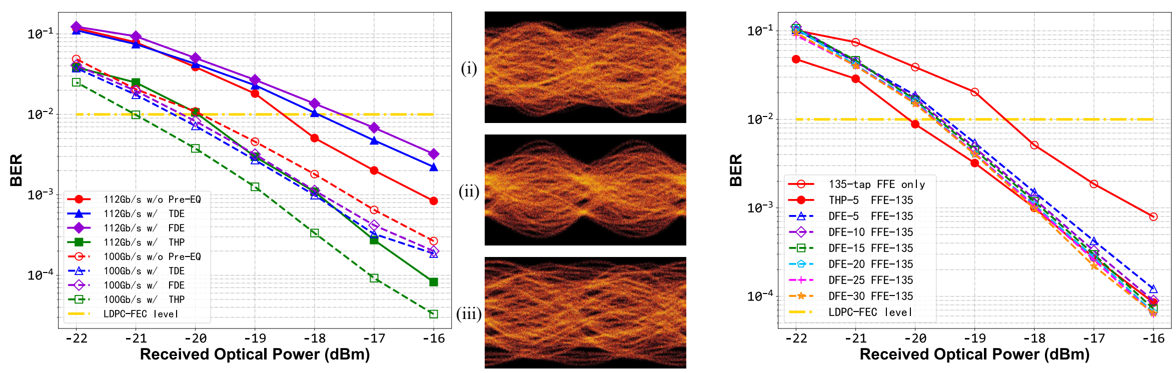
(a) (b)

Fig. 1: (a) Experimental setup for 112-Gb/s PAM-4 TDM-PON downstream transmission system; (b) System frequency response diagram.

The generation and recovery process of PAM-4 signal are depicted in the Tx and Rx off-line DSP block. At transmitter side, the pseudorandom bit sequence (PRBS) is generated and mapped to a random symbol sequence of PAM-4 format. Then three Pre-EQ schemes are considered and compared, namely Tomlinson-Harashima pre-coding, time-domain Pre-EQ (TDE) and frequency-domain Pre-EQ (FDE). At receiver side, the captured PAM-4 signal is resampled from 80-GSa/s to 56-GSa/s after timing recovery. And then channel estimation is performed. After that, FFE or DFE filter is used for post-equalization before PAM-4 de-mapping and BER calculation. The filter coefficients for THP are obtained from channel estimation, and the impulse response of time-domain FIR filter is equivalent to the coefficients of the post-FFE.

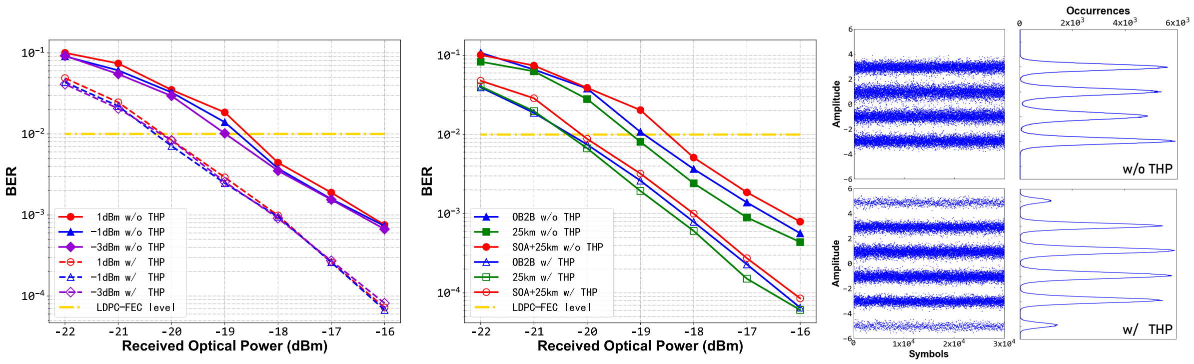
3. Experimental Results

We initially compare three Pre-EQ schemes in the 100-Gb/s and 112-Gb/s PAM-4 TDM-PON downstream transmission system with optimal post-FFE taps of 135 as Fig. 2(a) shows. Insets (i), (ii) and (iii) present Tx-side eye diagrams of the 112-Gb/s PAM-4 signal with TDE, FDE and THP, respectively. For 100-Gb/s PAM-4 signal, all the three pre-equalization schemes can improve the receiver sensitivity of the system at the LDPC-FEC threshold (1×10^{-2}). Among which THP works best, followed by TDE and FDE. For 112-Gb/s PAM-4 signal, significant improvement is also achieved with the help of THP. However, TDE and FDE offer no sensitivity improvement, which perform even worse than the case without any pre-equalization. It can be attributed to the much lower effective modulation power using TDE and FDE under more serious ISI cases. Fortunately, this issue can be avoided by the modulo function in THP method. The sensitivity is improved by 1-dB and 1.4-dB using THP for 100-Gb/s and 112-Gb/s PAM-4 signals with 135-tap post-FFE, respectively. Therefore, we adopt THP with the optimal feedback taps of 5 for pre-equalization in the following experiments. As we know, Tomlinson-Harashima precoding offers an alternative to the decision-feedback equalizer, which can eliminate the effect of the spectral zeros as effectively as DFE. As shown in Fig. 2(b), we compare the BER performance of THP and post-DFE with 135-tap post-FFE in the 112-Gb/s PAM-4 TDM-PON downstream link. Experimental results show that the DFE filter with more than 15-tap provides slightly better BER performance compared with THP when the ROP is -16 dBm, and there is almost no BER performance improvement while further increasing the tap number of DFE. As the received optical power decreases, the THP gradually shows its advantage over DFE because it avoids the error propagation problem of DFE by placing the feedback equalizer at the transmitter. As a result, THP offers ∼-20.2 dBm sensitivity at the LDPC limit of 1×10^{-2}, which is ∼0.5-dB better compared with 30-tap DFE.



(a) (b)

Fig. 2: (a) Measured BER vs. ROP for 100-Gb/s and 112-Gb/s PAM-4 signals using three pre-equalization schemes with 135-tap post-FFE; (b) Measured BER vs. ROP for 112-Gb/s PAM-4 signals using THP or post-DFE with 135-tap post-FFE.



(a) (b) (c)

Fig. 3: (a) Measured BER vs. ROP at different input power of SOA; (b) Measured BER vs. ROP at OB2B, 25-km SSMF and 25-km SSMF with SOA cases; (c) The amplitude distribution of 112-Gb/s PAM4 symbols with and without THP after 135-tap post-FFE as ROP is -16 dBm.

Considering the effectiveness of THP and DSP complexity at the ONU side, we adopt 5-tap THP at the OLT side and 135-tap FFE at the ONU side in the 112-Gb/s PAM-4 TDM-PON downstream experiment. Then we explore the sensitivity under different input power of SOA. For the signal without THP, the sensitivity drops to -18.5 dBm with 1 dBm SOA's input power, which is 0.4-dB worse than -3 dBm case as shown in Fig. 3(a). Note that decreasing the input power of SOA slightly improves the sensitivity at the expense of lower launch power. However, similar sensitivities are obtained within -3∼1 dBm input power for the signal with THP. Therefore, we set the SOA's input power at 1 dBm with the output power of 11.38 dBm to maximize the power budget. With the assistant of THP, the maximal power budget of 31.58-dB can be obtained, which is 1.68-dB higher than without THP case. We also compared the downstream sensitivity at back-to-back (B2B) and 25-km SSMF cases as Fig. 3(b) shows. Owing to the interaction between chirp effects of the modulator and chromatic dispersion, the sensitivity after 25-km transmission is slightly better than B2B case. Fig. 3(c) depicts the amplitude distribution of 112-Gb/s PAM-4 symbols with and without THP after 135-tap post-FFE while the ROP is -16 dBm in the downstream link, from which the signal quality improvement caused by THP can be clearly observed. Note that when THP is adopted at the Tx off-line DSP, the same modulo function is needed to decode extended data sequence at the receiver.

4. Conclusion

In this paper, we experimentally demonstrate the possibility of a 112-Gb/s/λ PAM-4 TDM-PON downstream transmission in O-band with 31.58-dB power budget using SOA and THP-based Pre-EQ at the OLT-side. Thanks to the THP, the receiver sensitivity is greatly improved with only simple FFE at the ONU side, which offers a promising solution for high-speed low-cost TDM-PON. Table 1 summarizes our results.

Table 1: Summary of 112-Gb/s/λ PAM-4 downstream link.

Transmission case	Equalization	Launch power	Sensitivity	Power Budget
25-km SSMF	FFE-135	1.90 dBm	-19.2 dBm	21.10 dB
	THP-5 + FFE-135	1.86 dBm	-20.4 dBm	22.26 dB
SOA+25-km SSMF	FFE-135	11.40 dBm	-18.5 dBm	29.90 dB
	DFE(135,30)		-19.7 dBm	31.10 dB
	THP-5 + FFE-135	11.38 dBm	-20.2 dBm	**31.58 dB**

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