C-Band Net-105-Gb/s PS-PAM-4 Transmission over 100-km SSMF Enabled only by Linear Equalizers with Weight Sharing

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Abstract *When transmission distances exceed 20 km, CD becomes a primary constraint in IM/DD systems. In this research, net-105-Gb/s PS-PAM-4 transmission over 100-km SSMF is enabled by only utilizing linear FIR pre-compensation and post-FFE. Furthermore, weight sharing is adopted to reduce $>$ 97% multiplication operations.*

Introduction

The rapid growth of cloud computing, Internet of Things (IoT), and virtual reality (VR) has created new demands for data center interconnects. High-order intensity modulation direct detection (IM/DD) schemes are popular due to their spectral efficiency and cost-effectiveness[1],[2]. However, chromatic dispersion (CD) induced power fading, combined with increasing baud rates and transmission distances, leads to more pronounced performance issues. This significantly limits the transmission distance and baud rate of IM/DD schemes.

To address the signal degradation from CD, dispersion compensating fiber, single sideband or vestigial sideband modulation, or Kramers-Kronig receiver can be employed. However, the main challenge for these methods is the high cost of implementation, incompatible with cost-sensitive IM/DD systems. As a result, researchers have turned their attention to digital signal processing (DSP) technology to mitigate CD-induced power fading in a cost-effective fashion. Decision feedback equalization (DFE) performed at the receiver is commonly used to address that concern. However, it is prone to error propagation. Tomlinson-Harashima precoding (THP) can circumvent error propagation, but introduces pre-coding loss and requires precise channel feedback[3],[4].

In this paper, we employ the finite impulse response filter based pre-electronic dispersion compensation with weight sharing (FIR-EDC-WS) to achieve 100-km transmission at a net rate of 105 Gb/s using PS-PAM-4. Implementing this FIR-EDC-WS at the transmitter makes it sufficient to utilize a feed-forward equalizer (FFE) also with weight sharing for adaptively equalizing the residual linear inter-symbol interference (ISI) at the receiver. The performed linear FIR-EDC is derived by small-signal analysis (SSA)[5]–[8]. WS[9],[10] for both transmitter- and receiver-side low-complexity linear equalizers is posed to further reduce the system's computational complexity substantially.

Principle of linear FIR-EDC-WS

The SSA-based FIR-EDC is a time-domain representative using FIR of the linear approximation of the inverse of CD response in the frequency domain[5]–[8]. Based on SSA[11], CD can be expressed simply using $\cos\theta|_{\theta=D\lambda^2\omega^2 L/4\pi c}$ where D is the CD coefficient, λ is the central wavelength, ω is the frequency of the modulated signal, L is the transmission distance along the fiber, and c is the light speed. Mathematically, its frequency-domain closed-form expression is given by[5]–[8]:

$$H(f) = \frac{1-\sin^{2n}(\theta)}{\cos(\theta)} + \sin^{2n}(\theta), \quad (1)$$

where n is the iteration index, and the larger the n is, the closer to $1/\cos\theta$ the $H(f)$ becomes, but requiring a higher digital-to-analog conversion (DAC) resolution. Therefore, the proposed FIR-EDC with finite taps is $h(t) = \mathcal{F}^{-1}\{H(f)\}$.

Without WS, the output $y(n)$ of FIR-EDC (FFE as well) can be expressed as:

$$y(n) = [h(0)...h(N-1)][x(n)...x(n-N+1]^T, \quad (2)$$

where N, h, and $x(n)$ are the number of taps, the weights, and input at n^{th} sample, respectively; $[\cdot]^T$ stands for the sum transpose operator. By applying WS, implemented by the k-means clustering algorithm here, the output of FIR-EDC-WS/FFE-WS can be given by:

$$y_{\mathrm{WS}}(n) = \sum_{i=1}^{N_c} w(i) x_c(n,i), \tag{3}$$

where N_c and $w(i)$ are the number of clusters and the centroid, respectively, and $x_c(n,i)$ is the summation of the input terms in $x(n)$ whose corresponding weights with similar values are clustered to the same centroid. Equalizer with WS explores fewer kernels to achieve efficient equalization by sharing the same kernel with different input signal terms. Thus, it naturally decreases the number of multiplication operations from N to N_c.

Experimental setup and results

The experimental setup and DSP block diagram are shown in Fig. 1. At the transmitter, PS-PAM-4 signal is generated offline where it is pulse-shaped using a raised cosine (RC) filter with a roll-off factor of 0.1, and subsequently processed by employing FIR-EDC-WS. Then the signal is forwarded to an arbitrary waveform generator operating at a sample rate of 120 GSa/s (AWG, Keysight M8194A). Amplified by an electrical amplifier (EA), the signal actuates a Mach-Zehnder modulator (MZM) to modulate a beam centered at 1550.12 nm. The modulated signal is subsequently transmitted over 100-km standard single-mode fiber (SSMF). At the receiver, the signal is amplified by an erbium-doped fiber amplifier (EDFA) and directly detected by a 70 GHz photodetector (PD). A variable optical attenuator (VOA) is employed to adjust the received optical power (ROP) for assessing the system's power budget. Ultimately, the detected signal is recorded by a 256-GSa/s oscilloscope (OSC, Keysight UXR0804A) and undergoes DSP procedures, including resampling, synchronization, and employing a simple FFE with a limited number of taps. Note that both FIR-EDC-WS and FFE-WS work at 2 samples per symbol. Finally, the normalized generalized mutual information (NGMI) is calculated to evaluate the system's performance, incorporating soft-decision forward error corrections (SD-FECs)[12]–[14]. The net rate can be calculated by the entropy (S) and baud rate (Bd) as:

$$\text{Net rate} = [S - (1-0.826) \times \log_2(M)] \times \text{Bd}. \tag{4}$$

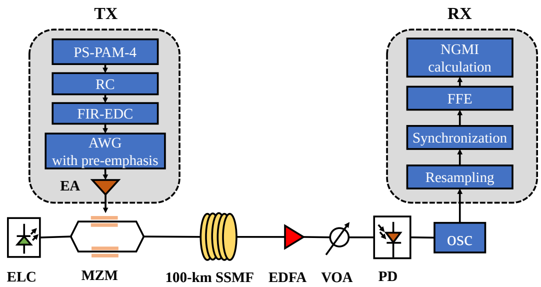

Fig. 1: Experimental setup and DSP.

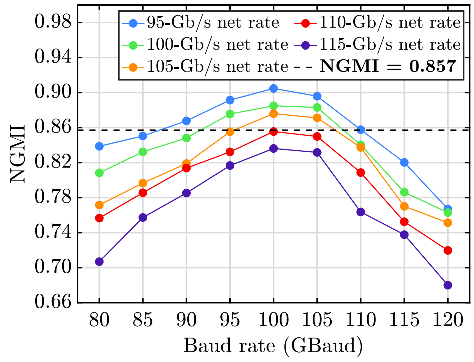

Fig. 2: Achievable NGMI of different net rates under Baud rate.

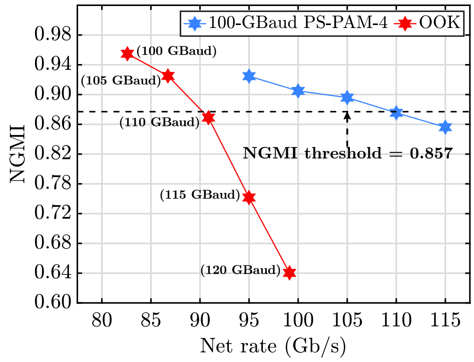

Fig. 3: Achievable NGMI of PS-PAM-4 and OOK with different net rates, using FIR-EDC.

According to Eq. 4, to achieve the same net rate, different combinations of baud rate and entropy can be applied. In order to evaluate the performance of various combinations, we first conduct a scan on the baud rates ranging from 80 Gbaud to 120 Gbaud, using 2501-tap FIR-EDC and 101-tap FFE. As shown in Fig. 2, at a certain net rate the achieved NGMI is increased from 80 GBuad to 100 GBaud and then decreased, a trade-off between entropy and bandwidth limitation in our setup. Hence, the baud rate of PS-PAM-4 is fixed at 100 GBaud. Under the NGMI threshold of 0.857, the maximal net rate achieved for 100-km PS-PAM-4 transmission is 105 Gb/s. In order to assess the superiority of the 100-GBaud PS-PAM-4 signal transmission scheme, the NGMI results for OOK signals with different baud rates are compared. The baud rates of OOK range from 100 GBaud to 120 GBaud in 5 GBaud

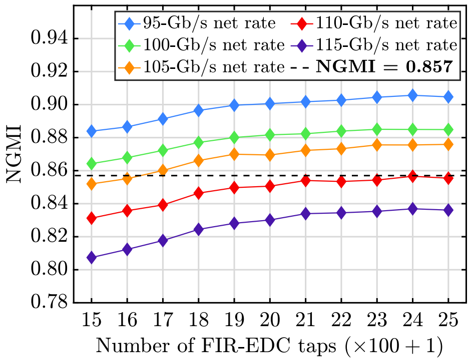

Fig. 4: Impact of the number of FIR-EDC taps on NGMI under differnet net rates.

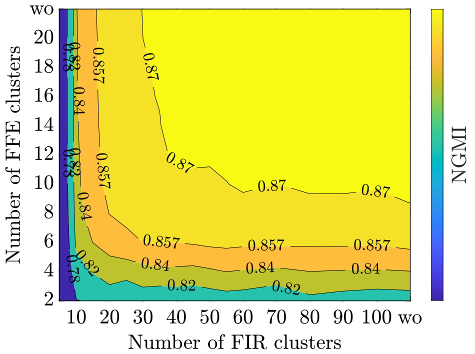

Fig. 5: Impact of the number of FIR-EDC-WS and FFE-WS clusters on NGMI at 105-Gb/s net rate.

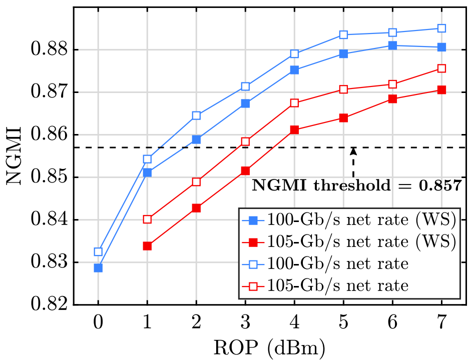

Fig. 6: NGMI versus ROP for PS-PAM-4 signals at 100-Gb/s and 105-Gb/s net rates with and without WS.

intervals, namely net rates ranging from 82.6 Gb/s to 99.12 Gb/s. Detailed results are illustrated in Fig. 3. As demonstrated in Fig. 3, the achieved net rate of the PS-PAM-4 is $>$ 105 Gb/s under the NGMI threshold, exhibiting an improvement of approximately 20 Gb/s relative to the net rate of the OOK modulation scheme.

Then, the relationship between the NGMI performance and the number of FIR-EDC taps is evaluated under different net rates. Our findings, as presented in Fig. 4, reveal that 1701 taps at the transmitter is actually sufficient to achieve the NGMI threshold at a net rate of 105 Gb/s for 100-km SSMF transmission. Moreover, NGMI performance saturates with 2301-tap FIR-EDC, which is also adopted for the following results. Next, we employ WS, namely FIR-EDC-WS and FFE-WS, to reduce the complexity of 2301-tap FIR-EDC and 101-tap FFE required by the system, as results shown in Fig. 5. Specifically, only 40 and 12 clusters for FIR-EDC-WS and FFE-WS are required to achieve the NGMI of more than 0.87, respectively, leaving a sufficient margin away from the threshold. Notably, this combination requires only 52 multiplications and saves the overall $>$ 97% multiplication operations compared with the use of 2301-tap FIR-EDC and 101-tap FFE without WS. Finally, we investigate the ROP budget of PS-PAM-4 over 100 km SSMF using equalization with WS and without WS. Figure 6 shows that at the NGMI threshold of 0.857, the required ROP at 100-Gb/s net rate is increased from 1.2 dBm for FIR-EDC to 1.7 dBm for FIR-EDC-WS, while at 105-Gb/s net rate it is increased the ROP from 3 dBm to 3.5 dBm. Although WS introduces a ROP cost of about 0.5 dB, it provides a significant reduction in the number of multiplication operations for equalization.

Conclusion

In this paper, a 105-Gb/s net-rate CD-aware PS-PAM-4 IM/DD transmission system over 100 km has been accomplished using linear FIR-EDC-WS and FFE-WS schemes. By employing the essential WS, the complexity of these schemes is significantly reduced with above 97% complexity in the required number of multiplications compared with FIR-EDC and FFE without WS, with an acceptable 0.5-dB ROP penalty. The use of FIR-EDC-WS and FFE-WS verifies the practicality of low-complexity C-band beyond net-100-Gb/s IM/DD transmission over 100-km SSMF.

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