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Optoelectronic Feedforward Equalization: Simple 1-tap Optical Delay Line and Ethernet-compliant Linear FFE Enabling C-band 100G PAM4 over ER+ distance

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Abstract *Ultimately low-complexity optoelectronic feedforward equalization (OE-FFE) scheme is investigated both analytically and experimentally for dispersion-limited high-speed IM/DD PAM4 systems. 6.7% HD-FEC-compliant BERs are achieved for C-band 100Gb/s and 112Gb/s over 50km with 1-tap optical delay line and 19-tap / 31-tap linear FFE only. ©2022 The Author(s)*

Introduction

100G-and-beyond intensity-modulation direct-detection (IM/DD) systems, e.g., with 4-ary pulse amplitude modulation (PAM4), are under active study, driven by the demand of high-capacity, cost/energy-efficient datacenter networks and access/edge networks [1, 2]. With increased fiber distance such as 40km or “extended reach (ER)” in IEEE 802.3 [3], double-sideband (DSB) IM/DD transmission in C-band and even edge wavelengths of O-band [4, 5] face a profound issue of chromatic dispersion (CD)-induced power fading. Efforts have been made to mitigate this issue in optical domain, from dispersion compensation fiber (DCF) to optical equalizers [6] and optical vestigial-sideband (VSB) filters [7, 8]. Yet it is difficult to achieve error-free performance for 100G-and-beyond PAM4 solely by optics. Alternatively, advanced digital signal processing (DSP) has become powerful in compensating the CD distortion, such as nonlinear feedforward equalizer (FFE) and decision-feedback equalizer (DFE), Tomlinson-Harashima precoding (THP) and/or sequence estimator (e.g., MLSE), possibly with additional optics [7-13]. However, the digital equalizer’s complexity is still high so far: the number of multiplications per PAM4 symbol (*NMPS*) can be >10 times of typical industry numbers for 100G Ethernet (10~30tap FFE plus 0~2tap DFE [14, 15]). Moreover, DFE/THP with long feedback filters usually suffers from circuit throughput bottleneck. On the coding side, hard-decision forward error correction (HD-FEC) is highly preferred over (although high-gain) soft-decision FEC for IM/DD systems [15].

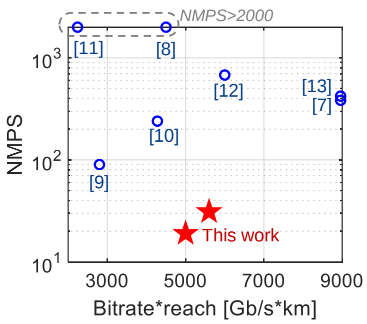

Fig. 1. Recent experiments of DCF-free C-band 100G DSB PAM4. NMPS: number of multiplication per PAM symbol in digital equalizer.

In essence, DD converts the CD channel, a linear all-pass system, to a non-minimum-phase system. This increases the complexity of DSP. To design a stable and low-complexity inverse system (“equalizer”), a promising path would be to combine pre-DD (optical) and post-DD (electronic) processors.

In this work, we present a joint optoelectronic feedforward equalization (OE-FFE) approach for low-complexity mitigation of CD distortion. A comprehensive and parameterized analytical model is provided, which can predict the system characteristics such as closed-form symbol error-rate (SER), meanwhile facilitating joint optics-electronics design & optimization. 6.7% HD-FEC-compliant bit error rates (BERs) are experimentally achieved for C-band 100Gb/s and 112Gb/s over 50km with simple 1-tap optical delay line and only 19-tap / 31-tap symbol-spaced linear FFE. Fig. 1 compares this work with prior works, showing advantage of OE-FFE approach in *NMPS*.

Concept of OE-FFE and analytical system performance

The concept of joint OE-FFE for IM/DD systems is illustrated in Fig. 2(a). DD converts the dispersive channel, a linear all-pass system, to a non-minimum-phase system with deep fading/ notches in the (RF) frequency response. To construct the inverse system efficiently, the optical part of OE-FFE pre-processes the incident signal for notch avoidance, so that the complexity of digital equalizer is considerably reduced and feedback paths (e.g., DFE) can be omitted. The

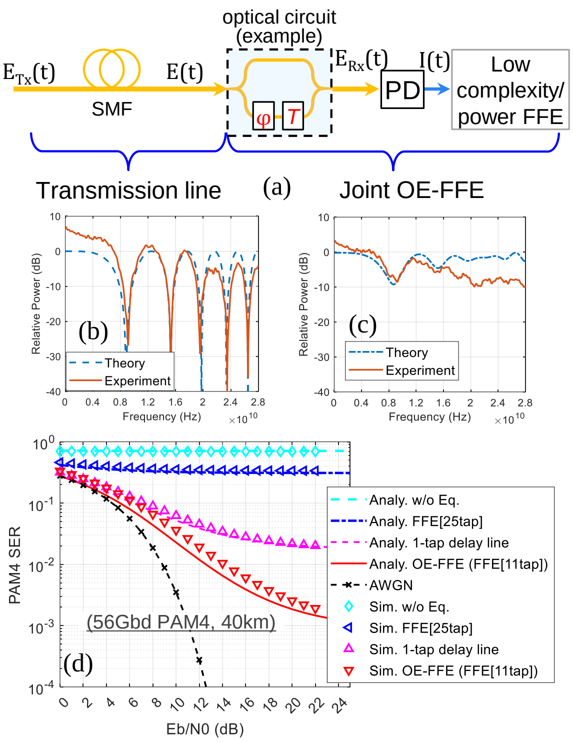

Fig. 2: (a) PAM4 system based on OE-FFE. SMF: single-mode fiber. (b)-(c) Theoretical and experimental frequency response of 56GBd PAM4 over 50km SMF, (b) without and (c) with the 1-tap delay line. (d) Analytical ("Analy.") and simulated ("Sim.") SER of 56GBd PAM4 over 40km SMF.

optical circuit should be simple, low-cost, and hopefully passive. One of the simplest realizations of the optical part is an optical single-tap delay line, shown in Fig. 1(b). It consists of an 1x2 power splitter, a phase shifter with φ shift, an optical delay *T*, and a 2x1 power coupler. It can be based on either free-space or waveguide components. Note that, the optical part is considerably simpler and potentially more cost-effective than a sharp optical VSB filter, whose complexity may be analogous to a many-tap optical FIR circuit. Parameters of OE-FFE such as φ, *T* and number of digital FFE taps would be jointly optimized according to the target CD range. Single-chip integrated OE-FFE could be realized, e.g., via silicon photonics.

Theoretical RF frequency response: to derive the IM/DD system response, we assume a small single-frequency RF signal $\sqrt{A+\cos(\omega t)}$ is input to the system. The optical circuit has an impulse response of $h(t)=\delta(t)+e^{j\varphi}\delta(t-T)$. The averaged RF power of PD output at angular frequency Ω is ∝ $\overline{[I(t)|_{\Omega}]^2}$. The photocurrent

$$I(t)|_{\Omega}=E_{Rx}(t)E_{Rx}^{*}(t)|_{\omega=\Omega} \quad (1)$$

where the complex envelope [16, 17]

$$E_{Rx}(t)=E(t)+e^{j\varphi}E(t-T) \quad (2)$$

$$E(t)\approx\frac{1}{4\sqrt{A}}\left(4A+e^{j\omega t}e^{j\theta}+e^{-j\omega t}e^{j\theta}\right) \quad (3)$$

$\theta=\omega^2\beta_2 L/2$ is fiber-induced phase shift (relative to the carrier) on the 2 sidebands. Theoretical frequency responses are then obtained by numerical integral; Figs. 2(b)-(c) show theoretical responses of 56GBd (112Gb/s) PAM4 over SMF of L=50km and β_2=-2.0407e-26 (equivalent dispersion is 16-ps/(nm*km)). *T* and φ of the 1-tap optical delay line were assumed to be 8ps and -0.65π respectively in Figs. 2(c)-(d). Without the optical circuit, 5 CD-caused spectral notches in the 1st Nyquist zone are seen in Fig. 2(b). They cannot be well-compensated by FFE due to severe noise enhancement. With the 1-tap delay line, these spectral zeros are removed as in Fig. 2(c), so that low-complexity digital FFE would suffice to handle remaining channel distortions.

Analytical SER/BER performance: suppose PAM4 symbols $\{b_k\}\in\{-3,-1,1,3\}$ are transmitted. The discrete-time signal $\{y_i\}$ at digital FFE output is modeled as:

$$y_i=\sum_{k=-\infty}^{\infty}b_k g_{i-k}+n_i \stackrel{\text{def}}{=} b_i g_0+v_i \quad (4)$$

v_i denotes the distortion, i.e., (residual) inter-symbol interference (ISI) plus additive noise. $\{g_k\}$ are the end-to-end channel impulse response (CIR), which can include the response of the receiver front-end and FFE. Here we assume the receiver front-end is ideal and employs the FFE based on minimum mean-square error (MMSE) criterion [18]. To derive SER, cumulative distribution function (CDF) of v_i, $F_{v_i}(x)=\Pr\{v_i<x\}$, is needed. Based on Gil-Pelaez theorem and [19],

$$F_{v_i}(x)\approx\frac{1}{2}-\frac{2}{\pi}\sum_{m=1,3,5\ldots}^{\infty}\frac{Im\{e^{-jm\omega x}\Phi_{v_i}(m\omega)\}}{m} \quad (5)$$

Where $\omega=2\pi/\tau$ and τ is a parameter governing the (frequency-domain) sampling rate. The characteristic function $\Phi_{v_i}(m\omega)$ of the distortion v_i is derived using the summation property [20]. Specifically, for PAM4, we have

$$\Phi_{v_i}(m\omega)=\prod_{k\neq 0}\frac{1}{2}[\cos(m\omega g_k)+\cos(3m\omega g_k)] +e^{-\frac{1}{2}\sigma^2 m^2\omega^2} \quad (6)$$

where σ^2 is the variance of noise. To facilitate calculation, we assume ISI is approximately finite-length (k=N_1~N_2), while $F_{v_i}(x)$ is truncated to m≤*M*. Parameters $\{N_1, N_2, M, \tau\}$ affect the accuracy of SER estimation (the larger the more accurate). Leveraging constellation symmetry, PAM4 SER is derived as a function of $F_{v_i}(x)$:

$$SER_{PAM4}=2\Pr\{v_i<2-3g_0|\,b_i=3\}+2\Pr\{v_i<-g_0\,|\,b_i=-1\}+2\Pr\{v_i>2-g_0\,|\,b_i=1\}$$

$$=\frac{1}{2}\{F_{v_i}(2-3g_0)+F_{v_i}(-g_0)+F_{v_i}(-2+g_0)\} \quad (7)$$

Finally, assuming 1 bit error per symbol error (e.g., by Gray coding), BER of PAM-N can be derived from SER as $BER=SER/\log_2 N$.

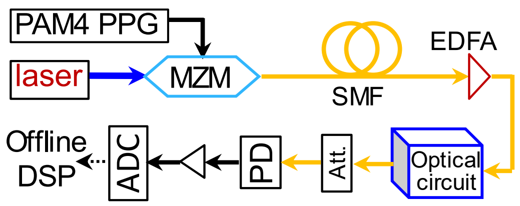

Fig. 3: Experimental setup. EDFA: Erbium-doped fiber amplifier. Att.: optical attenuator.

As an example, the analytical SER versus E_b/N_0 of a L=40km, 56GBd PAM4 system is depicted in Fig. 2(d), along with simulation results. For the analytical SER, N_1=-40, N_2=40, M=201, and τ=8. The number of symbol-spaced digital FFE taps were set to 25 or 11 in this example, whereas our parameterized model also supports other parameters. The theory predicts the effectiveness of joint OE-FFE: simple 1-tap optical delay line and only 11-tap digital FFE enable a reasonably-low system SER, and SER improvement of 2~3 orders of magnitude was achieved. Moreover, the results show that theory matches well with simulations.

Experimental demonstration

The experimental setup of OE-FFE enabled 100G PAM4 transmission is shown in Fig. 3. At the transmitter side, electrical 50GBd and 56GBd PAM4 were generated from a pulse pattern generator (PPG, Anritsu). The signal was modulated onto an optical carrier (NKT Coheras Basik) at ≈1547nm via a single-drive Mach-Zehnder modulator (MZM, 3dB bandwidth around 25GHz) biased around its quadrature point. The optical DSB PAM4 signal was then transmitted over 50km SMF to the receiver with optical amplification. At the receiver side, the PAM4 signal traversed the optical 1-tap delay line based on free-space components with delay (T) of about 8ps. Then the signal was detected by a 50GHz photodetector (PD) and captured by a 160GSa/s analog-to-digital converter (ADC, Agilent real-time oscilloscope) after an electrical amplifier. The digitized signal was processed offline, including resampling, synchronization, symbol-spaced RLS-FFE, and PAM4 demodulation. BER was assessed by direct error counting.

Figs. 2(b)-(c) show the experimental frequency response estimated from the received 112Gb/s PAM4 signal without and with the 1-tap delay line, respectively, after 50km transmission. The 1-tap delay line successfully removed the deep spectral notches caused by CD. The residual spectrum fluctuations or distortions would be suitably handled by the following digital FFE. The experimental frequency response match well with theoretical prediction.

Fig. 4(a) shows BER versus the number of taps of digital FFE after 50km and OE-FFE. For 100Gb/s system, BER lower than 6.7% HD-FEC limit (BER=4.5e-3 [14]) was achieved with 1-tap optical delay line and 19-tap linear FFE; for 112Gb/s system, 31-tap linear FFE was needed. Notably, these numbers of FFE taps (and *NMPS* of 19 & 31) are compliant with industry numbers.

BER versus PD input power after 50km transmission was also measured for 100Gb/s and 112Gb/s PAM4 systems, as shown in Fig. 4(b). 31-tap digital FFE was used in “w. OE-FFE” cases. The joint OE-FFE was a key for 50km transmission with low-complexity DSP. The inset shows the amplitude histogram of recovered 100Gb/s PAM4 with +3dBm PD input power. In the case of 100Gb/s system without OE-FFE, the optical 1-tap delay line was replaced by an optical bandpass filter, while digital DFE was used with 63-tap feedforward filter and 31-tap feedback filter, i.e., tripled complexity. Nevertheless, performance was far from satisfactory level due to severe CD-induced power fading and error propagation.

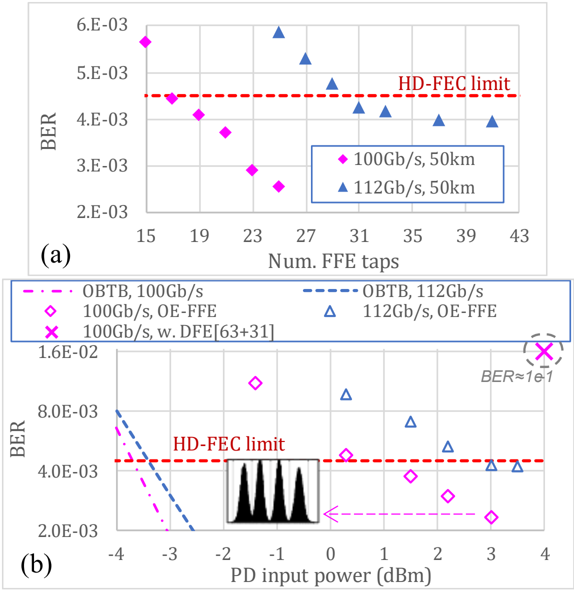

Fig. 4: (a) BER versus number of digital FFE taps (PD input power @ +3dBm). (b) BER versus PD input power, optical back-to-back (OBTB, without EDFA) and after 50km.

Conclusion

We have proposed the OE-FFE approach for CD distortion mitigation in IM/DD systems. An analytical system model is provided together with the closed-form SER/BER representation of PAM4, which is readily extendable to other modulation formats. We experimentally demonstrated its feasibility via DCF-free C-band 100Gb/s and 112Gb/s PAM4 transmission over 50km SMF (≈800ps/nm dispersion) with a simple optical 1-tap delay line and record-low 19-tap / 31-tap linear FFE.

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