Dispersion Compensation over C-band WDM Grid for 100Gb/s PAM4 System by Low-complexity Optoelectronic Feedforward Equalization (OE-FFE)

Paikun Zhu[1], Yuki Yoshida[1], Atsushi Kanno[2,1], Kouichi Akahane[1], and Ken-ichi Kitayama[3,1]
1. National Institute of Information and Communications Technology (NICT), Tokyo 184-8795, Japan
2. Nagoya Institute of Technology, Aichi 466-0061, Japan
3. Hamamatsu Photonics Central Research Laboratory, Shizuoka 434-8601, Japan
pkzhu3@nict.go.jp yuki@nict.go.jp

Abstract: We experimentally investigate OE-FFE-enabled C-band 100Gb/s/λ PAM4 transmission over 50km with different carrier frequencies and linewidths. 3.8-THz range on ITU-T G.694.1 grid is supported with a single 1-tap optical delay line and ≤32-tap digital FFE. © 2022 The Author(s)

1. Introduction

Intensity-modulation direct-detection (IM/DD) systems with data rates of 100Gb/s/λ and beyond, e.g., using 4-ary pulse amplitude modulation (PAM4) format, are energy- and cost-effective options for applications of datacenter interconnects (DCI) and edge cloud networks [1,2]. Meanwhile, the fiber distance in DCI of major cloud service providers can reach 40km or more (termed "ER" in IEEE standard) with possible proportion of >40% [3]. For high-bandwidth and/or extended-reach IM/DD systems, a main detrimental issue to the signal quality in C-band and even edges of O-band is the power fading induced by fiber chromatic dispersion (CD). To tackle this issue, both optical and electronic processing have attracted considerable attention. The optical methods [4, 5] usually enjoy advantages of a high bandwidth and low power consumption. On the other hand, in recent years, approaches relying on digital/electronic equalizers have been heavily discussed [6-8]; notable performance has been achieved very recently albeit at quite high complexity of receiver equalizer (and transmitter digital signal processing (DSP) as well). It would be debatable if the complexity is acceptable for practical deployment. For instance, the complexity of those digital equalizers usually reach 5~10 times that of industry practice for 100G Ethernet (i.e., up to 32 taps, specifically, 30 feedforward plus 2 decision-feedback taps [9, 10]) if the complexity is calculated by number of multiplications per PAM symbol (NMPS) and number of taps per symbol (NTPS).

In our recent work [11], we have showed the feasibility of a low-complexity joint optoelectronic feedforward equalization (OE-FFE) approach for CD-constrained IM/DD system. Distinct from previous works that empirically combined DSP and optics, e.g., for vestigial sideband (VSB) transmission [6], we provided a guiding theory of our proposed OE-FFE design. It was revealed that optics as simple as a 1-tap optical delay line (ODL) enables drastic reduction of digital equalizer complexity by removing all CD-induced spectral nulls, while the digital equalizer finely compensates for the residual frequency fluctuations. Consequently, OE-FFE enables hardware-friendly all-feedforward equalization without requiring more-complicated decision-feedback equalizer (DFE) or maximum likelihood sequence estimator (MLSE).

In this work, we further experimentally investigate wavelength/frequency and linewidth impact on 100Gb/s IM/DD PAM4 transmission over 50km single-mode fiber (SMF) with OE-FFE. It is shown that a set-and-forget 1-tap ODL with low-complexity digital FFE (≤32 taps) can cover 3.8THz range of C-band International Telecommunication Union (ITU-T) G.694.1 dense wavelength division multiplexing (DWDM) grid (191.4~195.2THz), which indicates great potential to support WDM transmission. Also, up-to-40MHz laser linewidth is investigated. It is found that 500-kHz linewidth is sufficient for the system, while 40MHz linewidth could support 8 channels within 2.6THz range.

2. Experimental Setup

The experimental setup of OE-FFE-based 100Gb/s IM/DD PAM4 transmission over 50km SMF is shown in Fig. 1. At the transmitter side, 50GBd electrical PAM4 signal was generated from a pulse pattern generator (PPG, Anritsu inc.). The peak-to-peak voltage of the electrical signal at PPG output was about 0.77V. No transmitter DSP was applied such as pulse shaping or pre-equalization. The signal was modulated onto an optical carrier tuned at different frequencies via a single-drive Mach-Zehnder modulator (MZM, 3dB bandwidth about 25GHz) biased around its quadrature point. Laser (Santec TLS-510) with different linewidths, namely 500kHz and 40MHz, were investigated; the wavelength accuracy was ±30pm according to the specification. The optical double-sideband (DSB) PAM4 signal with a launched power of ~2.5dBm was then transmitted over 50km SMF to the receiver after being amplified by an Erbium-doped fiber amplifier (EDFA). At the receiver side, the PAM4 signal was first processed by the optical part of OE-FFE, i.e., a 1-tap ODL based on free-space components. Its optical delay (T) was set to 10ps (corresponding to a free-spectral range (FSR) of 100GHz) based on performance in theory [11] and the compatibility to ITU WDM grid. Its phase shift φ was optimized only with the signal at 193.4THz, i.e., in a set-and-forget manner [12]. Subsequently, the signal was detected by a 50GHz photodetector (PD) and captured by a 256GSa/s analog-to-digital converter (ADC, Keysight oscilloscope) after RF amplification. The receiver-side offline DSP includes resampling with low-pass filtering, down-sampling to 1 sample per symbol, synchronization, symbol-spaced digital FFE (via recursive least squares adaptation), and PAM demodulation. Bit error rate (BER) was calculated via direct error counting.

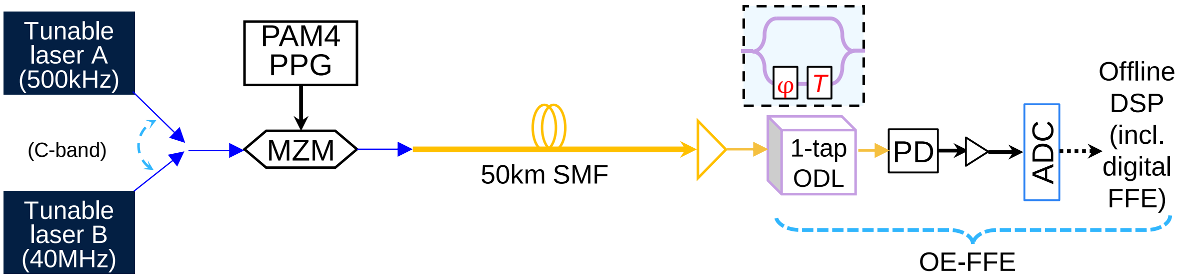

Fig. 1. Experimental setup of C-band OE-FFE-based 100Gb/s PAM4 over 50km SMF using laser with different frequency and linewidth. The inset shows the structure of the 1-tap ODL. φ: phase shift. T: optical delay.

3. Experimental Results and Discussion

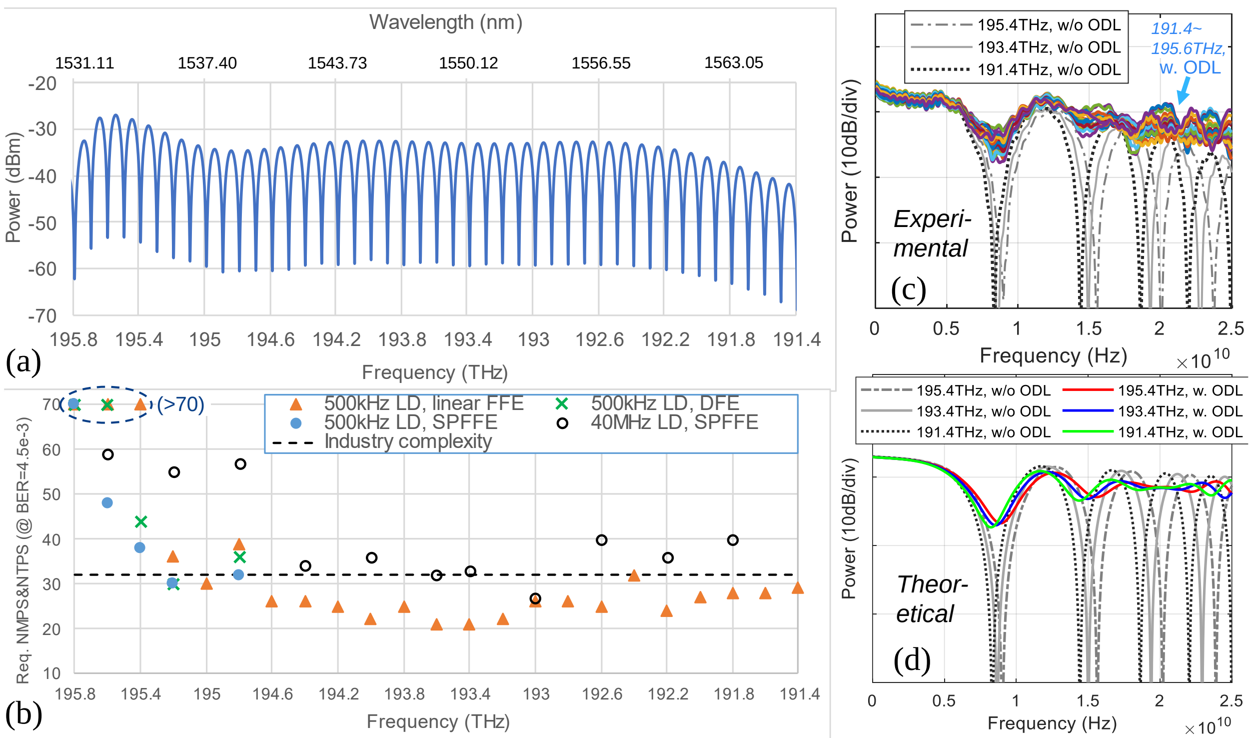

Fig. 2. Experimental results. (a) Optical spectra of ASE noise after passing through the 1-tap ODL. (b) Required NMPS&NTPS (@ BER=4.5e-3) versus signal frequency in OE-FFE-based 100Gb/s PAM4 over 50km SMF. LD: laser diode. SPFFE: simplified polynomial FFE [7]. "Industry complexity" corresponds to NMPS&NTPS=32 (i.e., 30 feedforward taps plus 2 decision-feedback taps [9, 10]). (c) Experimental system frequency responses at different frequencies in C-band. (d) Theoretical frequency responses at different frequencies in C-band. The wavelength-dependent CD coefficient assumed in the theory is D[ps/(nm·km)]=11+0.0622·(λ-1460) [13].

Fig. 2(a) depicts the optical spectra of amplified spontaneous emission (ASE) noise after traversing the 1-tap ODL. We first used the 500kHz laser as signal carrier and tuned it on the ITU-T G.694.1 DWDM grid with increments of 200GHz (note that, the system also supported increments of 100GHz). We measured the required NMPS & NTPS of digital FFE when the bit error rate (BER) was less than 4.5×10^{-3}, the 6.7% hard-decision forward error correction (HD-FEC) threshold [9]. Two different digital FFEs were investigated: one is a symbol-spaced linear FFE, while the other is a symbol-spaced simplified polynomial FFE (SPFFE) [7], a low-complexity variant of 2nd-order Volterra nonlinear FFE. The NMPS and NTPS of the linear FFE equal the number of taps N_1, while NMPS & NTPS of SPFFE equal the sum of number of linear taps and number of nonlinear taps N_1+N_2. Values of N_1 and N_2 were optimized toward minimum sum when SPFFE was used.

Fig. 2(b) shows the experimental results of required NMPS & NTPS versus signal frequency. Notably, even with linear FFE only, NMPS & NTPS ≤ 32 was achieved when signal frequency was from 191.4THz to 194.6THz with 500kHz laser linewidth. By allowing the use of nonlinear SPFFE, NMPS & NTPS ≤ 32 over 3.8THz (from 191.4THz to 195.2THz) was achieved. Further, by allowing more FFE taps, e.g., relaxing the criteria to "NMPS & NTPS ≤ 50", almost full C-band can be supported by OE-FFE except the very edge around 195.8THz or 1531nm, where severe BER floor occurred limited by the insufficient performance of the available EDFA. Even when the digital FFE in OE-FFE was replaced by a DFE, (although more complicated to implement in hardware) no advantage in complexity was brought as displayed by cross symbols in Fig. 2(b). This confirmed the benefit of OE-FFE architecture. Overall, the results indicated great potential to support WDM transmission by OE-FFE with a single fixed 1-tap ODL device.

Next, we changed the linewidth of signal carrier to 40MHz, and measured the required NMPS & NTPS for signals at different frequencies. As shown in Fig. 2(b), fluctuation of required NMPS & NTPS became larger which could be attributed to larger laser phase noise to amplitude noise translation [14]. Within 2.6THz range (from 191.8THz to 194.4THz), the required NMPS & NTPS was ≤40 for 8 channels.

In addition, with 500kHz-linewidth laser, the baseband system frequency responses measured from 191.4THz to 195.6THz are depicted in Fig. 2(c) in an overlapped manner. The measured frequency responses of the same system but without using the 1-tap ODL were also depicted in Fig. 2(c) by grey solid and dashed lines. Meanwhile, the theoretical frequency responses of the system are shown in Fig. 2(d) for reference. Experimental and theoretical results match well. Evidently, although the spectral positions of the nulls at different frequencies can be quite different after 50km transmission due to CD slope, a single 1-tap ODL removed all spectral nulls at all wavelengths/frequencies. The residual frequency fluctuations were approximate but having slight differences as predicted by theoretical responses in Fig. 2(d), which is because (*i*) CD values at different frequencies are different; (*ii*) there could be slight mismatch of laser frequency relative to the phase shift of 1-tap ODL. Also, the response of the ODL at different frequencies might not be exactly identical. Nevertheless, as shown in Fig. 2(b), these differences were well handled by the electronic part of OE-FFE (i.e., the adaptive digital FFE), which implies that the OE-FFE approach could also tolerate imperfections in practical situations to a certain extent.

4. Conclusion

We have experimentally investigated the impact of carrier frequency and linewidth on OE-FFE-based 100Gb/s IM/DD PAM4 system over 50km SMF. At 6.7% HD-FEC limit, 3.8-THz range on ITU-T G.694.1 DWDM grid has been supported with one set-and-forget 1-tap ODL and only ≤32-tap digital FFE, indicating great potential for low-complexity WDM transmission. Current results were mainly limited by the EDFA in our setup and further support of full C-band WDM grid is expected. When 40MHz laser was employed, larger performance fluctuation was observed than 500kHz laser; nevertheless 8 channels within 2.6THz range was supported with ≤40-tap digital FFE.

5. References

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