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Joint Hartley-domain and time-domain equalizer for a 200-G (4×56-Gbit/s) optical PAM-4 system using 10G-class optics

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Abstract: In this paper, we experimentally demonstrate a 200-G (4×56-Gbit/s) optical 4-level pulse-amplitude modulation (PAM-4) system using 10G-class optics over 10-km standard single-mode fiber and propose a joint Hartley-domain equalizer (HDE) and time-domain equalizer (TDE) algorithm for efficiently compensating the serious high-frequency distortions caused by the bandwidth-limited devices. To the best of our knowledge, the first HDE based on Hartley transform is designed for an optical PAM-4 system. Owing to the real-valued and self-inverse properties of the Hartley transform, the HDE has advantages in processing the real-valued PAM-4 signal. The experimental results show that the joint HDE and TDE algorithm has a better performance than only the HDE or only the TDE. Meanwhile, for obtaining a desired bit error rate, the computational complexity of the joint HDE and TDE algorithm is approximately 6% that of only the TDE with larger tap number. In conclusion, the joint HDE and TDE algorithm shows great potential for high-speed and cost-sensitive optical PAM-4 systems.

1. Introduction

In recent years, the data traffic of mobile Internet, cloud computing and high-definition TV is increasing rapidly, driving the development for massive data center. To satisfy the high-capacity data transmission of intra- and inter- data center, the short-reach optical interconnects (the length of fiber link is usually 500-m, 2-km or 10-km) using high-order modulation and wavelength division multiplexing (WDM) techniques have been extensively studied and applied [1–3]. The IEEE P802.3bs 200-G and 400-G Ethernet Task Force adopted 4-level pulse-amplitude modulation (PAM-4) WDM systems as an industrial standard to support 200-G and 400-G interfaces with data rate of 50-Gbit/s/λ or 100-Gbit/s/λ [4–6]. In the cost-sensitive optical interconnects, the low-cost 10G-class optics are preferred for Electrical-to-Optical (E/O) and Optical-to-Electrical (O/E) conversions [7–9]. Due to the limited bandwidth of 10G-class optics, 50-Gbit/s and 100-Gbit/s optical PAM-4 signals suffer from the serious high-frequency distortions, which requires the advanced equalizers for compensating the serious distortions to improve the transmission performance.

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The frequently-used equalizers include time-domain equalizer (TDE) and frequency-domain equalizer (FDE). TDE such as feed-forward equalizer (FFE) and decision feedback equalizer (DFE) is commonly employed to compensate the distortions for optical PAM-4 systems [10–12]. For coping with the serious distortions, the TDE with large tap number is required. However, the computational complexity of TDE increases with the tap number. Due to the limited computing source, TDE with large tap number is very difficult to implement in practice. FDE can be also valid for the PAM-4 systems, which has lower computational complexity than TDE [13–15]. However, FDE is realized by complex-valued fast Fourier transform (FFT), equalization, Hermitian symmetry, and inverse fast Fourier transform (IFFT) operations. Recently, fast Hartley transform (FHT) is proposed to replace the FFT for real-valued signal processing [16–18]. In this paper, we first design Hartley-domain equalizer (HDE) for real-valued PAM-4 systems. HDE is implemented by real-valued FHT, equalization, and FHT operations, which is more straightforward for handling the real-valued signal compared to FDE. However, it is worth noting that the performance of HDE is similar to that of FDE, but worse than that of TDE for compensating the serious high-frequency distortions.

To simultaneously achieve a good bit error rate (BER) performance and low computational complexity, a joint HDE and TDE algorithm is first proposed for optical PAM-4 system. We experimentally demonstrate 200-G (4×56-Gbit/s) optical PAM-4 system using 10G-class optics over 10-km standard single-mode fiber (SSMF) to verify the feasibility and performance of the joint HDE and TDE algorithm for compensating the serious high-frequency distortions. In the joint HDE and TDE algorithm, HDE can compensate the major inter-symbol interference (ISI) caused by the limited bandwidth. After the HDE, the residual distortion and enhanced noise still degrade the performance, which is then eliminated by the TDE. Because the major ISI has been compensated by the HDE, TDE with small tap number can be used to compensate the residual distortion, and the error probability of joint HDE and TDE algorithm is lower than that of only TDE. Therefore, the joint HDE and TDE algorithm has lower computational complexity compared to only TDE and better BER performance compared to only HDE and only TDE.

2. Principle of joint HDE and TDE algorithm

Figure 1 shows the designed structure of the joint HDE and TDE algorithm. The signal before equalizer is first fed into the HDE. Then, the TDE is used to compensate the residual distortions and enhanced noise after HDE. In this section, the principle of joint HDE and TDE algorithm is introduced.

2.1. Principle of HDE

In the HDE, the inverse discrete Hartley transform (IDHT) and DHT can be defined as [19]

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k [\cos(\frac{2\pi nk}{N}) + \sin(\frac{2\pi nk}{N})] \tag{1}$$

$$X_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n [\cos(\frac{2\pi nk}{N}) + \sin(\frac{2\pi nk}{N})] \tag{2}$$

where n and k is from 0 to $N-1$. Obviously, Hartley transform is a real-valued and self-inverse operation, which is suitable for signal processing in the real-valued PAM-4 system.

At the receiver end, the received PAM-4 signal after transmission link is expressed as

$$r(t) = h(t) \otimes x(t) + n(t) \tag{3}$$

where $h(t)$ is the channel impulse response, $x(t)$ is the transmitted PAM-4 signal, $n(t)$ is the noise component, and $\otimes$ is the convolution operation. After the Hartley transform, the received PAM-4

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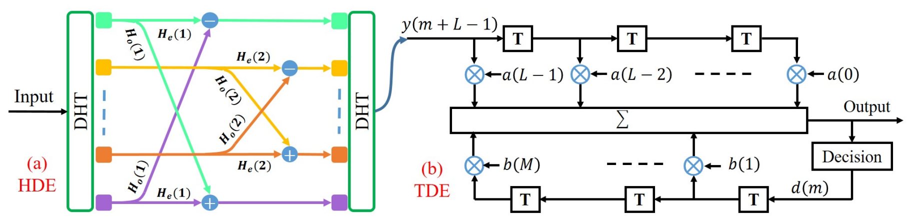

Fig. 1. The designed structure of joint HDE and TDE algorithm.

signal is converted into the Hartley-domain signal,

$$\begin{aligned} R(f) &= \int_{-\infty}^{+\infty} r(t) \times \mathrm{cas}(2\pi f t) dt \\ &= \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} h(\tau) x(t-\tau) d\tau \mathrm{cas}(2\pi f t) dt + N(f) \\ &= X(f) H_e(f) + X(-f) H_o(f) + N(f) \end{aligned} \tag{4}$$

where cas(.)=cos(.)+sin(.), $X(f) = \int_{-\infty}^{+\infty} x(t) \times \mathrm{cas}(2\pi f t) dt$, $H(f) = \int_{-\infty}^{+\infty} h(t) \times \mathrm{cas}(2\pi f t) dt$, $H_e(f) = [H(f) + H(-f)]/2$, $H_o(f) = [H(f) - H(-f)]/2$, and $N(f) = \int_{-\infty}^{+\infty} n(t) \times \mathrm{cas}(2\pi f t) dt$. The channel matrices $H_e(f)$ and $H_o(f)$ can be estimated by the training symbols, which are employed to compensate the channel distortions. Therefore, the HDE can be expressed as

$$X(f) = \frac{H_e(f)R(f) - H_o(f)R(-f)}{H_o^2(f) + H_e^2(f)} - \frac{H_e(f)N(f) - H_o(f)N(-f)}{H_o^2(f) + H_e^2(f)} \tag{5}$$

$$X(-f) = \frac{H_o(f)R(f) + H_e(f)R(-f)}{H_o^2(f) + H_e^2(f)} - \frac{H_o(f)N(f) + H_e(f)N(-f)}{H_o^2(f) + H_e^2(f)} \tag{6}$$

When signal-to-noise ratio (SNR) is high, $N(f)$ is small, which can be ignored compared to the signal. When SNR is low, the ignored $N(f)$ causes the error in HDE. Meanwhile, it is worth noting that if the power fading on some signal frequencies is serious, the $N(f)$ on the frequencies will be enhanced after HDE. However, $N(f)$ is hard to be accurately estimated, which is usually ignored in HDE. Therefore, HDE can be simplified as

$$X(f) \approx \frac{H_e(f)R(f) - H_o(f)R(-f)}{H_o^2(f) + H_e^2(f)} \tag{7}$$

$$X(-f) \approx \frac{H_o(f)R(f) + H_e(f)R(-f)}{H_o^2(f) + H_e^2(f)} \tag{8}$$

Based on the Eqs. (7) and (8), we design the structure of HDE, as shown in Fig. 1(a). First of all, the received signal is sent to DHT. After DHT, the signal can be equalized by the Eqs. (7) and (8) in the Hartley domain. Finally, the equalized signal is fed into the DHT again to generate the equalized signal after HDE.

2.2. Principle of TDE

Fig. 1(b) depicts the structure of (L, K) TDE with L-taps FFE and K-taps DFE, which is used to compensate the residual distortions after HDE. The output of the (L, K) TDE can be defined as

$$TDE_{\text{output}}(m) = \sum_{l=0}^{L-1} a(l) y(m+l) + \sum_{n=1}^{K} b(m) d(m-n) \tag{9}$$

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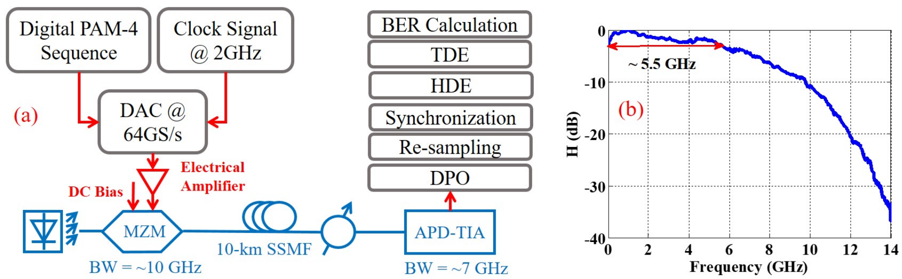

Fig. 2. (a) Block diagram of optical PAM-4 system with joint HDE and TDE algorithm using 10G-class optics; (b) Frequency response of the system.

where $a(l)$ is the weight of the l-th tap in FFE, $b(m)$ is the weight of the m-th tap in DFE, $y(m)$ is the input of the TDE, and $d(m)$ is the decision of $TDE_{\text{output}}(m)$. The decision operation in TDE has an ability to resist the enhanced noise caused by HDE.

Above all, the joint HDE and TDE algorithm can effectively compensate the serious high-frequency distortions and resist the enhanced noise.

3. Experimental setups and results

In this section, 4×56-Gbit/s optical PAM-4 system using 10G-class optics is experimentally implemented to verify the feasibility and performance of joint HDE and TDE algorithm for compensating the serious high-frequency distortions.

3.1. Experimental setups

Figure 2(a) shows the block diagram of 4×56-Gbit/s optical PAM-4 system with joint HDE and TDE algorithm using 10G-class optics. At the transmitter, the digital PAM-4 frame was generated by off-line processing using MATLAB. In one frame, 20 payload symbols and 2 training symbols were transmitted. For realizing precise HDE, the length of one PAM-4 symbol was set to 4096. The total length of prefix and suffix was set to 16 for resisting a part of ISI. The generated digital PAM-4 frame was uploaded into digital-to-analog converter (DAC) with the resolution of 8 bit, maximum sampling rate of 64 GSa/s, and 3-dB bandwidth of 16 GHz. The resampling operation was applied to the generated digital PAM-4 frame making the symbol rate of the electrical PAM-4 signal was 28 GBaud. Therefore, the link rate of electrical PAM-4 signal was 56-Gbit/s and its net data rate was 50.7 Gbit/s ($28 \times 2 \times 20/22 \times 4096/4112 \approx 50.7$ Gbit/s). The electrical amplifier with 3-dB bandwidth of 25 GHz amplified the generated electrical signal. Four external cavity lasers (ECLs) were used to generate four optical carriers with a spacing of 50 GHz from 1550.13 to 1551.33 nm. The amplified electrical signal was modulated to the optical carriers by an Mach-Zehnder modulator (MZM) with 3-dB bandwidth of ~10 GHz. Finally, the generated optical 4×56 Gbit/s optical PAM-4 signal with the power of 4 dBm was fed into the 10-km SSMF. The total loss of 10-km SSMF was approximately 2 dB. The equivalent 3-dB bandwidth caused by chromatic dispersion of 10-km SSMF is approximately 13.55 GHz, which can be calculated by $f_{3dB} = 1/\sqrt{|8\pi\beta_2 L|}$ where $\beta_2 = -21.66$ ps^2/km and L is the fiber length [20].

At the receiver, a variable optical attenuator (VOA) was used to adjust the received optical power (ROP). The WDM Demux with a spacing of 50 GHz was employed to implement the demultiplexing of the 4×56 Gbit/s optical PAM-4 signal. For higher receiver sensitivity, an APD with TIA was employed to converted the optical signal into an electrical signal, which has a 3-dB bandwidth of ~7 GHz. The converted electrical signal was fed into 100-GSa/s real-time oscilloscope (Tektronix DPO72004C) with 3-dB bandwidth of 20 GHz to implement analog-to-digital conversion (ADC). Fig. 2(b) depicts the measured frequency response of the

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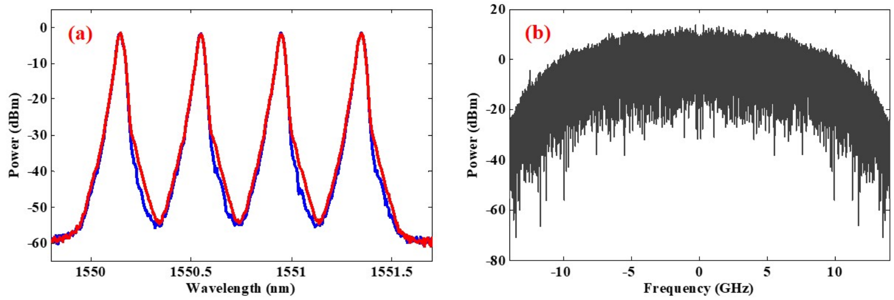

Fig. 3. (a) Optical spectrum of optical carriers (blue lines) and 4×56-Gbit/s optical PAM-4 signal (red lines); (b) Electrical spectrum of 56-Gbit/s PAM-4 signal.

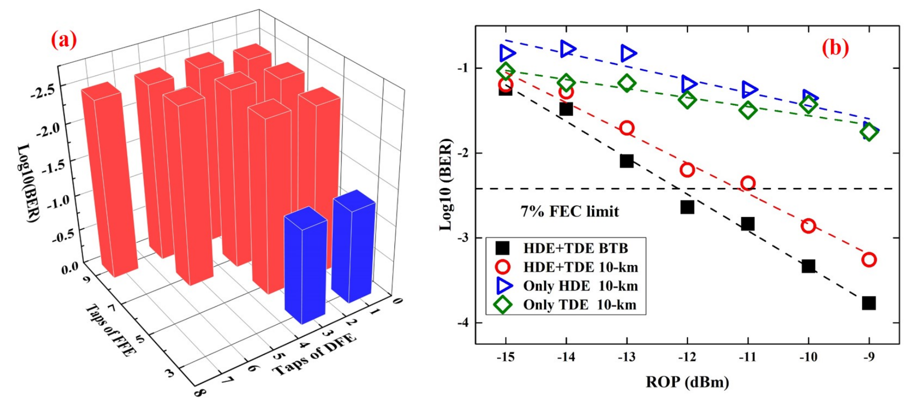

Fig. 4. (a) BER against tap number of FFE-DFE in joint HDE and TDE algorithm; (b) BER versus the ROP for the joint HDE and (5, 1) TDE algorithm, only HDE, and only (5, 1) TDE, respectively.

system with an equivalent 3-dB bandwidth of ~5.5 GHz. The recovered digital signal was decoded by off-line processing, including resampling, time synchronization, HDE, TDE and BER calculation. TDE compensated the serious distortions in collaboration with the HDE, which adopted FFE-DFE with recursive least square (RLS) adaptive algorithm. The RLS adaptive algorithm has fast convergence time and steady state mean square error, which is suitable for the high-speed optical PAM-4 systems [21].

3.2. Experimental results

Figure 3(a) depicts optical spectra of optical carriers (blue lines) and 4×56-Gbit/s optical PAM-4 signals (red lines). The resolution of the optical spectra is 0.03 nm. The measured four wavelengths of the 4×56-Gbit/s optical PAM-4 signals are approximately 1550.13, 1550.53, 1550.93, and 1551.33 nm, respectively. Fig. 3(b) shows the electrical spectrum of 56-Gbit/s PAM-4 signal. The total bandwidth of 56-Gbit/s electrical PAM-4 signal is 28 GHz. The baseband bandwidth of 56-Gbit/s electrical PAM-4 signal is 14 GHz, which is much higher than the equivalent 3-dB bandwidth of the system. Therefore, the 56-Gbit/s PAM-4 signal suffers serious high-frequency distortion due to the limited bandwidth. In the following, we firstly investigate the performance of joint HDE and TDE algorithm for 56-Gbit/s optical PAM-4 system in detail and verify the feasibility of joint HDE and TDE algorithm for 4 × 56-Gbit/s optical PAM-4 system.

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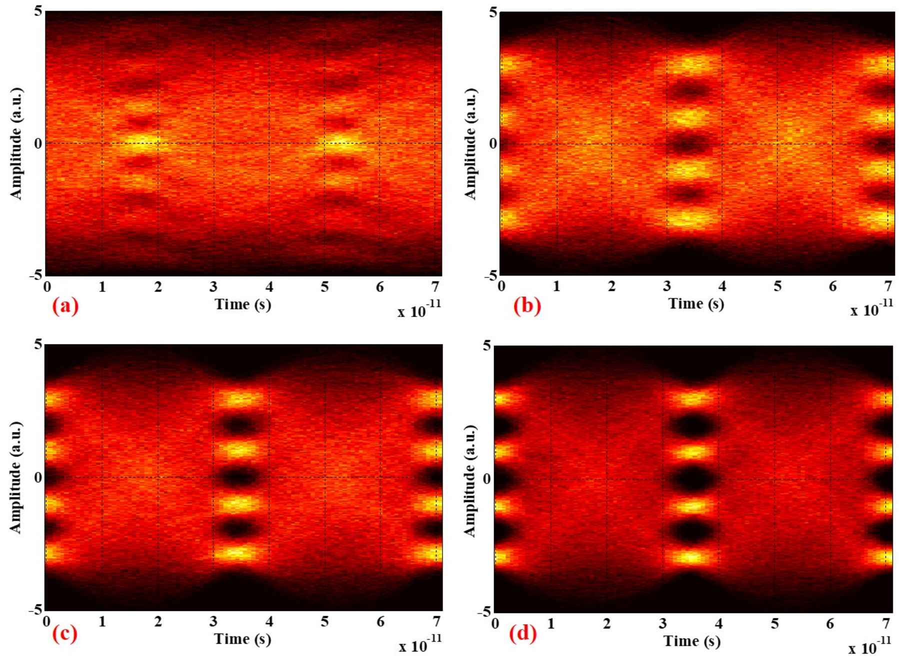

Fig. 5. The eye diagram of the recovered PAM-4 at the ROP of −9 dBm after 10-km SSMF transmission. (a) Without equalization; (b) After only HDE; (c) After only (5, 1) TDE; (d) After joint HDE and (5, 1) TDE algorithm.

Figure 4(a) reveals BER against tap number of FFE-DFE in joint HDE and TDE algorithm for 56-Gbit/s optical PAM-4 system at the ROP of −11 dBm after 10-km SSMF transmission. 56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm can achieve the BER near the 7% forward error correction (FEC) limit. The BER performance is not obviously improved by increasing the taps. In joint algorithm, (5, 1) TDE has the same tap number but better performance compared to (3, 3) TDE. The possible reason is that 1-tap DFE has less error propagation. For taking into account both the performance and complexity, (5, 1) TDE is employed in the joint HDE and TDE algorithm in the following. Fig. 4(b) depicts the BER performance of 56-Gbit/s optical PAM-4 system with different equalization algorithms. For 56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm, the required ROP at the 7% FEC limit was measured to be approximately −12 dBm and −11 dBm after BTB and 10-km SSMF transmission, respectively. The maximum power penalty for 10-km SSMF transmission was approximately 1 dB compared to BTB transmission. The 56-Gbit/s optical PAM-4 system with only HDE or only (5, 1) TDE cannot achieve 7% FEC limit at the ROP of −9 dBm. The BER performance of 56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm is much better than that with only HDE or only (5, 1) TDE.

Figure 5 shows the eye diagrams of the recovered PAM-4 signals at the ROP of −9 dBm after 10-km SSMF transmission. (a) Without equalization; (b) After only HDE; (c) After only (5, 1) TDE; (d) After joint HDE and (5, 1) TDE algorithm. As Fig. 5(a) shows, the eye diagram of the recovered PAM-4 signal without equalization appears seven levels due to the serious ISI caused by the limited bandwidth. As Fig. 5(b) shows, although ISI can be effectively compensated by the HDE, the noise on the high-frequency part is enhanced. Therefore, the eye diagram of the recovered PAM-4 signal after only HDE is indistinct. In only (5, 1) TDE, DFE can restrain the enhanced noise induced by FFE. Therefore, as Fig. 5(c) depicts, the eye diagram of the recovered

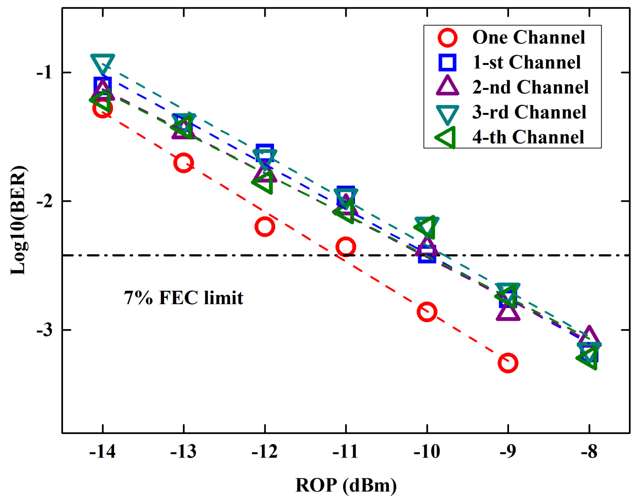

Fig. 6. BER against ROP for 4×56-Gbit/s PAM-4 system with joint HDE and TDE algorithm after 10-km SSMF transmission.

PAM-4 signal after only TDE is more clear than that after only HDE. In joint HDE and (5, 1) TDE algorithm, (5, 1) TDE is used to cancel the residual ISI and enhanced noise after HDE. As shown in Fig. 5, the most distinct eye diagram is obtained by the joint HDE and (5, 1) TDE algorithm. Therefore, 56-Gbit/s optical PAM-4 system with joint HDE and TDE algorithm can achieve the best BER performance.

To further improve the capacity, the 4×56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm was experimentally demonstrated. Fig. 6 shows BER against ROP for the 4×56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm after 10-km SSMF transmission. For 4×56-Gbit/s optical PAM-4 system, the required ROP at the 7% FEC limit is measured to be approximately −10 dBm after 10-km SSMF transmission. Compared to 56-Gbit/s optical PAM-4 system, the power penalty for 4×56-Gbit/s optical PAM-4 system is approximately 1 dB. The experimental results demonstrate that the joint HDE and (5, 1) TDE algorithm is feasibility for the bandwidth-limited 4×56-Gbit/s optical PAM-4 system using the 10G-class optics.

4. Comparisons between joint HDE and TDE algorithm and only TDE algorithm

In this section, we will give the detailed comparisons of BER performance and computational complexity between joint HDE and TDE algorithm and only TDE algorithm

4.1. Comparisons of BER performance

Figure 7(a) depicts the comparison of BER performance between joint HDE and (5, 1) TDE algorithm and only TDE for the 56-Gbit/s optical PAM-4 system. When only TDE is employed, BER performance improves with the increase of the tap number. However, (35, 1) TDE has the same BER performance with (45, 1) TDE. This is because the distortions have been effectively compensated by (35, 1) TDE. At the 7% FEC limit, the receiver sensitivity of 56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm is approximately 2 dB and 1 dB higher than that with only (15, 1) and (25, 1) TDEs, respectively. The 56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm has almost the same receiver sensitivity at the 7% FEC limit compared to 56-Gbit/s optical PAM-4 system with only (35, 1) TDE. However, at the BER

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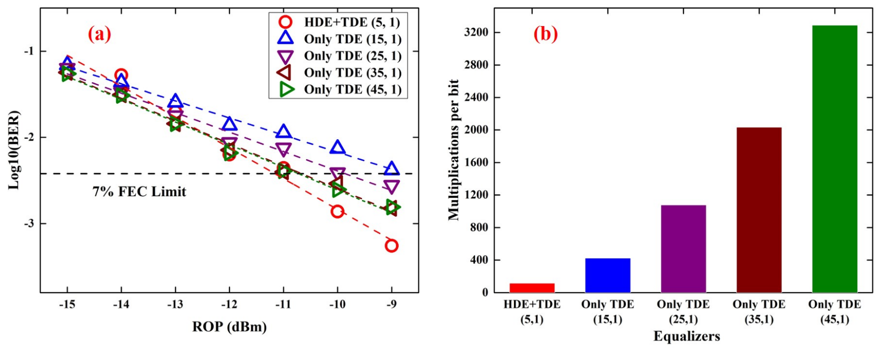

Fig. 7. (a) The comparison of BER performance between joint HDE and (5, 1) TDE algorithm and only TDE; (b) The comparison of computational complexity between joint HDE and (5, 1) TDE algorithm and only TDE.

lower than the 7% FEC limit, the receiver sensitivity of 56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm is higher than that with only (35, 1) TDE. When the ROP is smaller than −12 dBm, the BER performance of 56-Gbit/s optical PAM-4 system with joint HDE and (5, 1) TDE algorithm is worse than that with only (35, 1) TDE. This is because the low SNR causes large equalization error in HDE, which coincides with the theoretical analysis in Section 2. However, we usually consider the ROP for obtaining the BER at and below 7% FEC limit. Therefore, the joint HDE and TDE algorithm has better performance compared to only TDE.

4.2. Comparisons of computational complexity

The computational complexity of the equalizers can be measured in terms of the number of real-valued multiplications per bit. As shown in Fig. 1(a), HDE requires two FHTs and one equalization operation. The computational complexity of FHT is approximately $N\log_2 N$ where N is the length of FHT [19]. The computational complexity of the equalization operation is $2N$. Therefore, the computational complexity of HDE mainly depends on the computational complexity of two FHTs, which can be expressed as

$$C_{\mathrm{HDE}} = 2N\log_2 N/(N\log_2 M) = 2\log_2 N/\log_2 M \tag{10}$$

where M is the size of constellation. As shown in the Ref. [2], the computational complexity of conventional FDE is $4\log_2 N/\log_2 M$ when the complex FFT and IFFT are employed. Therefore, the computational complexity of HDE is half of that of conventional FDE.

As described above, (L, K) TDE uses L-taps FFE and K-taps DFE with RLS adaptive algorithm for high-speed bandwidth-limited optical PAM-4 system. The computational complexity of RLS adaptive algorithm is approximately $[3(L+K)^2 + 4(L+K)] \times F$ and the computational complexity of FFE-DFE is approximately $(L+K) \times F$ where F is the frame length1. Therefore, the computational complexity of (L, K) FFE-DFE with RLS adaptive algorithm can be expressed as [21]

$$C_{\mathrm{TDE}} = [3(L+K)^2 + 5(L+K)]F/(F\log_2 M) = [3(L+k)^2 + 5L + 5K]/\log_2 M \tag{11}$$

Figure 7(b) depicts the comparison of computational complexity between joint HDE and (5, 1) TDE and only TDE. The computational complexity of TDE increases with the increase of taps. In joint HDE and (5, 1) TDE algorithm, the tap number is much smaller than that in only TDE to achieve the desired BER. The total number of real-valued multiplications per bit is 117 in joint HDE and (5, 1) TDE algorithm. When (35, 1) TDE is used, the total number of real-valued multiplications per bit is 2034, which is almost twenty times of that in joint HDE and (5, 1) TDE algorithm. In conclusion, the joint HDE and (5, 1) TDE algorithm has both better performance and lower computational complexity compared to the only TDE.

5. Conclusion

In this paper, we propose the joint HDE and TDE algorithm for efficiently compensating the serious high-frequency distortions in the 200-G (4×56-Gbit/s) optical PAM-4 system using 10G-class optics. For eliminating the distortions, the joint HDE and TDE algorithm has better performance compared to only HDE and only TDE. Meanwhile, for obtaining a desired BER, the computational complexity of the joint HDE and TDE algorithm can be approximately 6% that of only TDE with larger tap number. Therefore, the joint HDE and TDE algorithm can effectively compensate the serious high-frequency distortions with low computational complexity. By using the joint HDE and TDE algorithm, 200-G (4×56 Gbit/s) PAM-4 signal over 10-km SSMF is experimentally implemented, which shows its potential for high-capacity short-reach optical interconnects.

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References

1. K. Zhong, X. Zhou, J. Huo, C. Yu, C. Lu, and A. P. T. Lau, "Digital Signal Processing for Short-Reach Optical Communications: A Review of Current Technologies and Future Trends," J. Lightwave Technol. **36**, 377–400 (2018).
2. K. Zhong, X. Zhou, T. Gui, L. Tao, Y. Gao, W. Chen, J. Man, L. Zeng, A. P. T. Lau, and C. Lu, "Experimental study of PAM-4, CAP-16, and DMT for 100 Gb/s short reach optical transmission systems," Opt. Express **23**, 1176–1189 (2015).
3. J. Shi, J. Zhang, N. Chi, and J. Yu, "Comparison of 100G PAM-8, CAP-64 and DFT-S OFDM with a bandwidth-limited direct-detection receiver," Opt. Express **25**, 32254–32262 (2017).
4. IEEE 802.3 ETHERNET WORKING GROUP, http://www.ieee802.org/3/bs/.
5. J. Wei, Q. Cheng, R. V. Penty, I. H. White, and D. G. Cunningham, "400 Gigabit Ethernet Using Advanced Modulation Formats: Performance, Complexity, and Power Dissipation," IEEE Commun. Mag. **53**, 182–189 (2015).
6. C. Xie, "Datacenter Optical Interconnects: Requirements and Challenges," in IEEE Optical Interconnects Conference (OI) (IEEE, 2017), pp. 37–38.
7. F. Li, J. Yu, Z. Cao, J. Zhang, M. Chen, and X. Li, "Experimental Demonstration of Four-Channel WDM 560 Gbit/s 128QAM-DMT Using IM/DD for 2-km Optical Interconnect," J. Lightwave Technol. **35**, 941–948 (2017).
8. W. Yan, T. Tanaka, B. Liu, M. Nishihara, L. Li, T. Takahara, Z. Tao, J. C. Rasmussen, and T. Drenski, "100 Gb/s Optical IM-DD Transmission with 10G-Class Devices Enabled by 65 GSamples/s CMOS DAC Core," in Optical Fiber Communication Conference (Optical Society of America, 2013), paper OM3H.1.
9. T. Bo, B. Kim, and H. Kim,"28-Gbps VCSEL-based Optical Access Network with >14-dB Power Budget Using 10G-Class Optical Components," in Opto-Electronics and Communications Conference (IEEE, 2017), pp.1–3.
10. J. Wei, K. Grobe, C. Wagner, E. Giacoumidis, and H. Griesser, "40 Gb/s Lane Rate NG-PON using Electrical/Optical Duobinary, PAM-4 and Low Complex Equalizations," in Optical Fiber Communication Conference (Optical Society of America, 2016), paper Tu3C.5.
11. J. Zhang, J. S. Wey, J. Yu, Z. Tu, B. Yang, W. Yang, Y. Guo, X. Huang, and Z. Ma, "Symmetrical 50-Gb/s/λ PAM-4 TDM-PON in O-band with DSP and Semiconductor Optical Amplifier Supporting PR-30 Link Loss Budget," in Optical Fiber Communication Conference (Optical Society of America, 2018), paper M1B.4.
12. K. Zhong, X. Zhou, Y. Wang, J. Huo, H. Zhang, L. Zeng, C. Yu, A. P. T. Lau, and C. Lu, "Amplifier-Less Transmission of 56Gbit/s PAM4 over 60km Using 25Gbps EML and APD," in Optical Fiber Communication Conference (Optical Society of America, 2017), paper Tu2D.1.
13. A. Nuwanpriya, S. Ho, J. Zhang, A. J. Grant, and L. Luo, "PAM-SCFDE for Optical Wireless Communications," J. Lightwave Technol. **33**, 2938–2949 (2015)
14. K. Matsumoto, Y. Yoshida, A. Maruta, A. Kanno, N. Yamamoto, and K. Kitayama, "On the Impact of Tomlinson-Harashima Precoding in Optical PAM Transmissions for Intra-DCN Communication," in Optical Fiber Communication Conference (Optical Society of America, 2017), paper Th3D.7.

Optics EXPRESS

15. I. Lyubomirsky and W. A. Ling, "Advanced Modulation for Datacenter Interconnect," in Optical Fiber Communication Conferenc (Optical Society of America, 2016), paper W4J.3.
16. M. S. Moreolo, R. Muñoz, and G. Junyent, "Novel Power Efficient Optical OFDM Based on Hartley Transform for Intensity-Modulated Direct-Detection Systems," J. Lightwave Technol. **28**, 798–805 (2010).
17. J. Zhou, Y. Yan, Z. Cai, Y. Qiao, and Y. Ji, "A Cost-Effective and Efficient Scheme for Optical OFDM in Short-Range IM/DD Systems," IEEE Photon. Technol. Lett. **26**, 1372–1374 (2014).
18. M. S. Moreolo, J. M. Fàbrega, F. J. Vílchez, L. Nadal, and G. Junyent, "Experimental demonstration of a cost-effective bit rate variable IM/DD optical OFDM with reduced guard band," Opt. Express **20**, B159–B164 (2012)
19. R. N. Bracewell,"The fast Hartley transform," Proc. IEEE **72**, 1010–1018 (1984).
20. D. Hsu, C. Wei, H. Chen, J. Chen, M. C. Yuang, S. Lin, and W. Li,"21 Gb/s after 100 km OFDM long-reach PON transmission using a cost-effective electro-absorption modulator," Opt. Express **18**, 27758–27763 (2010)
21. S. Haykin, *Adaptive Filter Theory* (Prentice Hall, 1993), Chap. 9.