C-Band PAM-4 Transmission Over 60-km SSMF Using Weight-Sharing Nonlinear Weighted DFEs

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Abstract—**Two weight-sharing nonlinear weighted DFEs are proposed for C-band 100-Gbit/s PAM-4 transmission over 60-km SSMF, one of which using absolute terms shows >26% complexity reduction compared with other nonlinear DFEs under 7% HD-FEC BER limit.**

Keywords—4-level pulse amplitude modulation (PAM-4), improved weighted decision-feedback equalizer (IWDFE), weight-sharing

I. Introduction

Intensity modulation and direct detection (IM/DD) system is regarded as the most cost-effective option in short-reach communication scenarios such as datacenter interconnects and access networks since it features the advantages of low cost, high energy efficiency, and small form factors [1], [2]. Among different spectrally efficient formats, 4-level pulse amplitude modulation (PAM-4) is preferred owing to the balance between performance and complexity [1], [2]. However, apart from the bandwidth limitation of optoelectronics devices, the chromatic dispersion (CD) and nonlinearities related to modulation and detection deteriorate the signal quality of IM/DD systems in the C-band [3]−[11]. Moreover, the interaction of CD and square-law detection also causes severe frequency selective power fading, which limits the available signal bandwidth and prohibits high-speed signal transmissions over longer fiber reach [3]−[11].

In contrast to impairment compensation techniques employing costly optoelectronics devices in the C band, digital signal processing (DSP) based equalization techniques are more attractive since they can keep the IM/DD system flexile and cost effective. Among various conventional equalizers, including feed-forward equalizer (FFE), polynomial/Volterra FFE (PFFE/VFFE) [3], [4], decision-feedback equalizer (DFE) [5], and polynomial/Volterra DFE (VDFE) [6]−[8], VDFE outperforms others attributed to the joint compensation for the memory nonlinearities and CD-induced power fading. Compared with neural network (NN) based nonlinear equalizers, the VDFE can also offer a better compromise between performance and computational complexity in bandwidth-limited IM/DD systems [8]. However, similar as DFE, the VDFE suffers from error propagation in the case of wrong decisions [9], [10]. To avoid error propagation, the decision-feedback filter of VDFE can be removed to the transmitter side named Volterra THP (VTHP) [9]. Nevertheless, a precise feedback of the kernels of the decision-feedback filter from the receiver to the transmitter is required for the VTHP scheme. To limit the error propagation and avoid kernel feedback, an improved weighted Volterra DFE (IWVDFE) has been proposed in a C-band 100-Gbit/s PAM-4 transmission system over 60-km standard single-mode fiber (SSMF) [10], achieving superior performance to the conventional VDFE. In addition to the equalization performance, the computational complexity, which is related to the power consumption of the DSP module, should also be considered. As a result, considering both the equalization performance and computational complexity of the IWVDFE is highly desired for the PAM-4 IM/DD systems.

In this paper, to further reduce the equalization complexity of the compensation for CD and nonlinear distortions, we introduce the absolute term and weight-sharing strategy in our previous proposed IWVDFE [10] and propose two weight-sharing WDFEs including weight-sharing IWVDFE (WS-IWVDFE) and weight-sharing absolute-term-based improved weighted DFE (WS-AT-IWDFE) in a C-band 100-Gbit/s PAM-4 transmission system over 60-km SSMF. Systematic investigation of the 60-km SSMF system based on various nonlinear DFEs, including VDFE, absolute-term-based DFE (ATDFE) [7], IWVDFE [10], AT-IWDFE, WS-VDFE [7], WS-ATDFE [7], WS-IWVDFE, and WS-AT-IWDFE, are carried out based on the complexity analysis and bit error rate (BER) measurement. Besides, simple diagonal pruning is employed to reduce the trivial cross-beating nonlinear terms of all nonlinear DFEs without sacrificing performance. Experimental results show that the equalizers with and without weight-sharing can achieve similar BER performance, while the weight-sharing one can significantly reduce the number of kernels or the equalization complexity. Among all the low-complexity weight-sharing nonlinear DFEs, the proposed WS-IWVDFE can achieve the best BER performance, while the proposed WS-AT-IWDFE can yield considerably lower complexity at the expense of a slight degradation in BER performance as compared to the WS-

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IWVDFE. Under the 7% hard-decision forward error correction (HD-FEC) BER limit of 3.8×10^{-3}, the proposed WS-AT-IWDFE requires the lowest number of real-valued multiplications of 30 and reduces the computational complexity by 97.4%, 26.8%, and 97.4% in comparison with the WS-VDFE, WS-ATDFE, WS-IWVDFE, respectively.

II. PRINCIPLE OF WS-IWVDFE AND WS-AT-IWDFE

To effectively compensate for the CD-induced power fading and nonlinear impairments, the diagonally-pruned IWVDFE with the advantage of reducing the error propagation probability can be applied in IM/DD systems. To simultaneously equalize the pre-cursor linear and nonlinear impairments and provide robustness against clock jitter, $T/2$ symbol-space VFFE is also included in the IWVDFE. Thus the nth sample of the output of diagonally-pruned IWVDFE can be expressed as [10]:

$$\begin{aligned} y(n) &= \sum_{k=0}^{N_1-1} h_1(k)x(2n-k) + \sum_{k=1}^{D_1} w_1(k)\tilde{y}(n-k) \\ &+ \sum_{q=0}^{Q-1}\sum_{k=0}^{N_2-1-q} h_2(k,q)x(2n-k)x(2n-k-q) \\ &+ \sum_{u=0}^{U-1}\sum_{k=1}^{D_2-u} w_2(k,u)\tilde{y}(n-k)\tilde{y}(n-k-u) \end{aligned} \tag{1}$$

where x is the received signal sampled at $T/2$ symbol space, h_K and N_K are the K^{th}-order (K = 1, 2) kernel and memory length of the VFFE, respectively, w_K and D_K are the K^{th}-order kernel and memory length of the IWVDFE, respectively. Q and U represent the pruning factors, which are used to prune the trivial nonlinear terms. The soft-decision feedback symbol $\tilde{y}(n)$ is a combination of the previous equalizer output $y(n)$ and the previous hard-decision output $\hat{y}(n)$, which can be expressed as [6], [10]:

$$\begin{aligned} \tilde{y}(n) &= f(\gamma_n)\hat{y}(n) + \left[1-f(\gamma_n)\right]y(n) \\ &= y(n) + f(\gamma_n)\left[\hat{y}(n)-y(n)\right] \end{aligned} \tag{2}$$

where γ_n and $f(\gamma_n)$ are the reliability value and the compressed sigmoid nonlinear function [6], [10], respectively, which can be calculated by:

$$\gamma_n = \begin{cases} 1-\left|y(n)-\hat{y}(n)\right|, \text{if } \left|y(n)\right| < M-1 \\ 1, \quad \text{else} \end{cases} \tag{3}$$

$$f(\gamma_n) = \frac{1}{2}\left(\frac{1-\exp\left[-a(\frac{\gamma_n}{b}-1)\right]}{1+\exp\left[-a(\frac{\gamma_n}{b}-1)\right]}+1\right) \tag{4}$$

where M is the level of the PAM symbols, a is a positive integer defining the steepness of the function $f(\gamma_n)$ and b with $0 < b \leq 1$ is a compression factor. The input γ_n can be directly mapped to the output $f(\gamma_n)$ after obtaining the pre-look-up table related to the parameters a and b.

By replacing the cross-beating terms in diagonally-pruned IWVDFE by the absolute terms [3], [4], the equalized output of the AT-IWDFE can be obtained and is given by:

$$\begin{aligned} y(n) &= \sum_{k=0}^{N_1-1} h_1(k)x(2n-k) + \sum_{k=1}^{D_1} w_1(k)\tilde{y}(n-k) \\ &+ \sum_{q=0}^{Q-1}\sum_{k=0}^{N_2-1-q} h_2(k,q)\left|x(2n-k)+x(2n-k-q)\right| \\ &+ \sum_{u=0}^{U-1}\sum_{k=1}^{D_2-u} w_2(k,u)\left|\tilde{y}(n-k)+\tilde{y}(n-k-u)\right| \end{aligned} \tag{5}$$

Compared with IWVDFE, the computational complexity of AT-IWDFE can be significantly reduced since the absolute operation can be implemented by an addition operation instead of a multiplication operation. The total numbers of kernels in diagonally-pruned VDFE, ATDFE [7], IWVDFE, AT-IWDFE are the same as $L = L_1 + L_2$, where $L_1 = N_1+D_1$ and $L_2 = Q(2N_2-Q+1)/2+U(2D_2-U+1)/2$.

For simplicity, we rewrite Eq. (1)/ Eq. (5) as:

$$y(n) = \sum_{l=0}^{L-1} h(l)x_L(n,l) \tag{6}$$

where $h(l)$ and $x_L(n, l)$ (l = 0, 1,..., L-1) are the kernels and their corresponding input signal terms in Eq. (1)/Eq. (5), respectively. After applying k-means clustering algorithm [7], [11] to obtain the cluster centers from the estimated kernels of the IWVDFE/AT-IWDFE, the output of proposed WS-IWVDFE/WS-AT-IWDFE can be expressed as:

$$y(n) = \sum_{i=0}^{C-1} h_C(i)x_C(n,i) \tag{7}$$

where $h_C(i)$ and C are the cluster centers (i.e., new kernels after clustering) and the number of clusters obtained by the k-means clustering algorithm, respectively. $x_C(n, i)$ is the sum of the corresponding input signal terms in Eq. (6), with their kernels belonging to the ith cluster with a cluster center of $h_C(i)$. The required number of real-valued multiplications (RNRM) for the proposed WS-IWVDFE and WS-AT-IWDFE are summarized and compared with other nonlinear DFEs [7] as the results shown in Table 1. Details of the complexity analysis can be found in [7]. Clearly, the nonlinear WDFEs only require one more real-valued multiplication to obtain the feedback symbol $\tilde{y}(n)$ compared to the nonlinear DFEs.

TABLE 1. COMPLEXITY COMPARISON OF DIFFERENT NONLINEAR DFES.

Equalizer	RNRM
VDFE [7]	L_1+2L_2
ATDFE [7]	L
IWVDFE [10]	L_1+2L_2+1
AT-IWDFE	L+1
WS-VDFE [7]	C+L
WS-ATDFE [7]	C
Proposed WS-IWVDFE	C+L+1
Proposed WS-AT-IWDFE	C+1

III. EXPERIMENTAL SETUP AND RESULTS

The performance of the proposed WS-IWVDFE and WS-AT-IWDFE is evaluated in a C-band 100-Gbit/s PAM-4 transmission system over 60-km SSMF. Fig. 1 shows the experimental setup and the employed DSP. At the transmitter, a pseudo random bit sequence (PRBS) is firstly generated and mapped to PAM-4 symbols. The PAM-4 symbols are then up-sampled and pulse-shaped with a rectangular filter at 4 samples per symbol. The shaped PAM-4 signal is fed into an

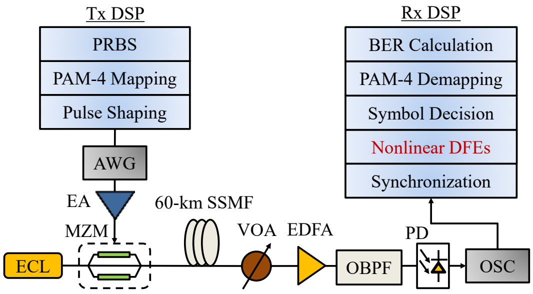

Fig. 1. Experimental setup and the employed DSP of 100-Gbit/s PAM-4 IM/DD system.

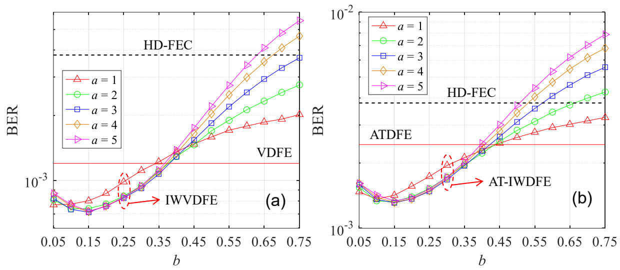

Fig. 2. BER as a function of compression factor b at different a using (a) IWVDFE and (b) AT-IWDFE.

arbitrary waveform generator (AWG, Keysight 8199A) operating at 200 GSa/s. After amplified by an electrical amplifier (SHF S807), the PAM-4 signal is used to drive a 35-GHz Mach-Zehnder modulator (MZM, Thorlabs LN05S-FC) biased at a quadrature point of around 1.4 V for electrical-optical conversion. The optical carrier is generated from an external cavity laser (ECL) at 1550.12 nm. After 60-km SSMF transmission without any dispersion compensation, a variable optical attenuator (VOA) is inserted to sweep the received optical power (ROP) of the received signal, which is then detected by a photodetector (PD, XPDV2120RA). An Erbium doped fiber amplifier (EDFA) followed by an optical band-pass filter (OBPF) is employed to boost the power into the PD up to 7 dBm owing to the lack of a trans-impedance amplifier (TIA). Finally, the detected electrical PAM-4 signal is captured and stored by a real-time oscilloscope (OSC) operating at 160 GSa/s for subsequent off-line DSP procedures including resampling to 2 samples per symbol, synchronization, equalization with the proposed WS-IWVDFE or WS-AT-IWDFE, symbol decision, PAM-4 demapping, and BER calculation. In the training process, 10000 training symbols are firstly transmitted to obtain the kernel coefficients of different equalizers based on the recursive least-squares (RLS) algorithm [7], which keep unchanged in the equalization process.

The parameters of the different equalizers are firstly optimized in a 100-Gbit/s PAM-4 system over 60-km SSMF at a ROP of -10 dBm. Based on the optimized parameters $N_1 = 74$, $N_2 = 74$, $Q = 13$, $D_1 = 32$, $D_2 = 20$, and $U = 9$ for the VDFE and ATDFE as presented in [7], the measured BERs as a function of the compression factor b at different a for the IWVDFE and AT-IWDFE are shown in Figs. 2(a) and 2(b), respectively. It can be observed that: 1) Owing to the reduction of error propagation probability, the optimal BERs of IWVDFE and AT-IWDFE are reduced by a factor of around two compared to the VDFE and ATDFE, respectively. 2) The performance of the IWVDFE is better than that of AT-IWDFE,

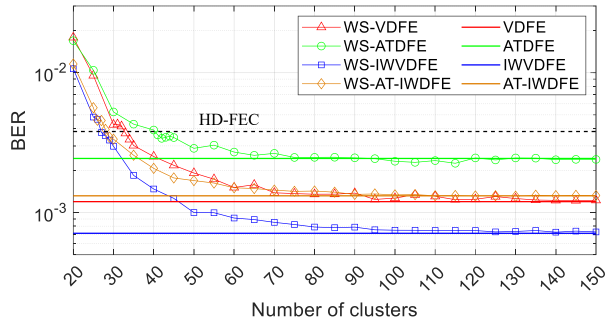

Fig. 3. BER versus the number of clusters for different equalizers.

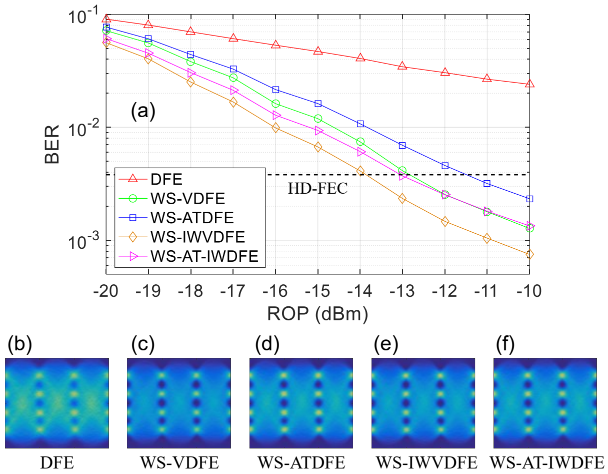

Fig. 4. (a) BER versus ROP using linear DFE and different weight-sharing nonlinear DFEs after 60-km SSMF transmission; (b) recovered eye diagrams of PAM-4 signals using different DFEs at a ROP of -10 dBm.

at the cost of higher computational complexity. 3) Based on the BER results, $a = 3$ and $b = 0.15$ are chosen for both IWVDFE and AT-IWDFE.

The numbers of cluster centers and their values (i.e., kernels of weight-sharing equalizers) of the WS-IWVDFE and WS-AT-IWDFE are optimized based on the estimated kernels of the IWVDFE and AT-IWDFE, respectively. Fig. 3 shows the measured BER versus the number of clusters for the WS-IWVDFE and WS-AT-IWDFE using the k-means clustering algorithm after 60-km SSMF transmission at a ROP of -10 dBm. The results of the WS-VDFE and WS-ATDFE proposed in [7] are also included for comparison. The following observations could be made: 1) The BER firstly decreases as the number of cluster centers increases for all weight-sharing equalizers. 2) The BER performance of all the weight-sharing equalizers comes to a standstill at 100 clusters, which is comparable to that of 1134-kernel nonlinear DFEs without weight-sharing. This can be attributed to the fact that a large number of kernels with similar values can be clustered into a smaller number of new kernels to reduce the kernel redundancy. 3) To satisfy the 7% HD-FEC BER threshold of 3.8×10^{-3}, the required numbers of kernels of the WS-VDFE, WS-ATDFE, WS-IWVDFE, and WS-AT-IWDFE can be reduced to 33, 41, 27, 29 at least, respectively. 4) As a result, the proposed WS-AT-IWDFE with 30 real-valued multiplications per symbol can reduce the computational complexity by 97.4%, 26.8%, and 97.4% compared with 1167, 41, 1162 real-valued multiplications per symbol of the WS-VDFE, WS-ATDFE, WS-IWVDFE, respectively.

Finally, the transmission performance of the proposed WS-IWVDFE and WS-AT-IWDFE is evaluated using only 100 kernels. Fig. 4(a) shows the measured BER versus the ROP using linear DFE and different weight-sharing nonlinear DFEs for 100-Gbit/s PAM-4 signal transmission over 60-km SSMF. The recovered eye diagrams of different DFEs at a ROP of -10 dBm are also presented in Figs. 4(b)–4(f). It can be seen that the BER of linear DFE cannot reach the 7% HD-FEC limit of 3.8×10^{-3}. Among all weight-sharing nonlinear DFEs, the proposed WS-IWVDFE can achieve the best BER performance and more than 0.8-dB improvement in receiver sensitivity over the others, while the proposed WS-AT-IWDFE yield much lower complexity at the expense of a slight performance degradation compared to the WS-IWVDFE.

IV. Conclusions

In this work, we have proposed and experimentally demonstrated a WS-IWVDFE and a WS-AT-IWDFE in a C-band 100-Gbit/s PAM-4 transmission system over 60-km SSMF. Among all the nonlinear DFEs, the proposed WS-IWVDFE with a reduction of the number of kernels can achieve the best BER performance similar to the IWVDFE. Under the 7% HD-FEC BER limit of 3.8×10^{-3}, the proposed WS-AT-IWDFE requires the lowest number of real-valued multiplications of 30 and saves 97.4%, 26.8%, and 97.4% real-valued multiplications in comparison with the WS-VDFE, WS-ATDFE, WS-IWVDFE, respectively.

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