Chromatic Dispersion Compensation With Feed Forward Equalizer and Decision Feedback Equalizer for Manchester Coded Signals

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***Abstract*—We investigate the performance of electronic chromatic dispersion compensation of 10-Gb/s Manchester coded optical signal using a feed forward equalizer (FFE) and decision feedback equalizer (DFE). Utilizing offline signal processing, the performances of FFE-DFE with different number of taps and input sampling rates under both cases of single-ended and balanced detection are compared. Experimental results show that the transmission distance of Manchester coded signal can be increased by a factor of three with four-sample-per-symbol FFE-DFE.**

***Index Terms*—Chromatic dispersion (CD), decision feedback equalizer (DFE), electronic dispersion compensation (EDC), feed forward equalizer (FFE), Manchester coding.**

I. Introduction

MANCHESTER code, which has one transition within every encoded bit period, is an attractive modulation format for various applications in optical fiber communication systems [1]–[10]. Compared with the conventional non-return-to-zero (NRZ) code, Manchester code has rich clock component and enables simple clock recovery and level recovery [1]. Besides, it has the feature of zero dc content, which makes it highly tolerant to signal intensity fluctuation when differential detection is used [2]. Bearing these advantages, Manchester code was extensively studied in high-speed burst mode transmission systems [3]–[5]. Besides, it has also found application in wavelength-division-multiplexed passive optical network (WDM-PON). Having equal power in every bit, Manchester code has been employed as the downstream signal format in WDM-PONs so as to facilitate upstream data transmission, via re-modulating the downstream optical carrier at the optical network units (ONUs) [6], [7]. In frequency domain, the main lobe of the Manchester coded signal is concentrated at the frequency that equals its data rate. Hence, such intrinsic property could effectively alleviate the optical beat noise between the optical line terminal and the ONUs in bidirectional WDM-PONs [8], [9]. In particular, one of its variants, the phase-shift-keying-Manchester signal [10], has been shown to have much stronger tolerance to the beat interference noise, compared with other modulation formats.

Nevertheless, Manchester code offers the aforementioned advantages at the expense of broader signal bandwidth, which is twice as that of the conventional NRZ signal. Therefore, the chromatic dispersion (CD) tolerance of the Manchester signals is only one fourth of their NRZ counterparts, which limits their practical applications. To mitigate this limitation, it has been proposed to incorporate duobinary coding into the Manchester signal [10] so as to improve its CD tolerance. However, the proposed Manchester-duobinary transmitter was very complex and the reported CD tolerance of 10-Gb/s Manchester-duobinary signal was roughly 50 km (equivalent to an residual CD value of 850 ps/nm), which still could not fulfill the requirement for modern metro and long-reach access networks.

With the recent advent of low-cost high-speed electronics, electronic dispersion compensation (EDC) has become a cost-effective technique to dynamically compensate CD accumulated in optical transmission systems and networks. At the receiver side, EDC can be realized by employing an analog feed forward equalizer (FFE) and/or decision feedback equalizer (DFE) [12], [13]. Compared with digital maximum-likelihood sequence estimation, FFE-DFE is relatively simple and easy to implement, especially for high bit rate signals. Its CD compensation capability was demonstrated for various modulation formats [14]–[16]. However, there is yet no report for EDC with FFE-DFE for Manchester coded signal.

In this paper, we experimentally investigate the performance of FFE-DFE for mitigating CD accumulated in Manchester signal, for both cases of single-ended detection (SD) and balanced detection (BD). According to Nyquist criterion, a sampling rate of 4 samples/bit is needed to fully reconstruct the waveform of the Manchester signal, which means the best performance of FFE-DFE can be achieved when the FFE takes four samples from each bit. To compromise between complexity and performance, we also show and compare the results for FFE-DFE at a sampling rate reduced to 2 samples/bit.

II. Experimental Setup

Fig. 1 shows the experimental setup to evaluate the CD compensation capability of FFE-DFE for optical Manchester signal. In the transmitter, the electrical Manchester signal was generated by a typical Manchester encoder, which took the exclusive OR (XOR) of two input signals, one of which was a 10.709-Gb/s NRZ signal carrying $2^{15}-1$ pseudorandom binary sequence, and the other was its clock signal. The signal bandwidth was

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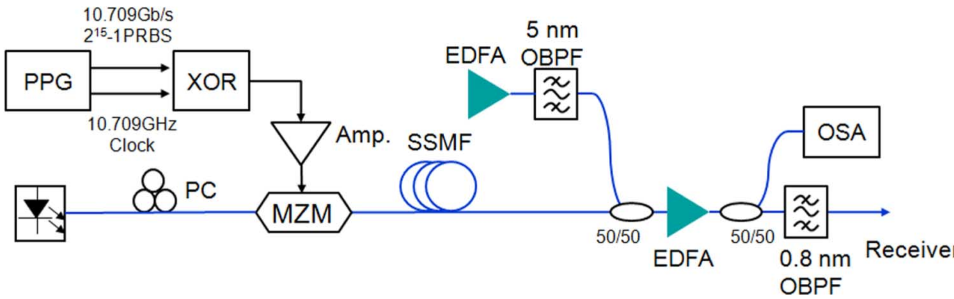


Fig. 1. Experimental setup. PPG: pattern generator, XOR: exclusive-OR, OSA: optical spectrum analyzer, OBPF: optical bandpass filter.

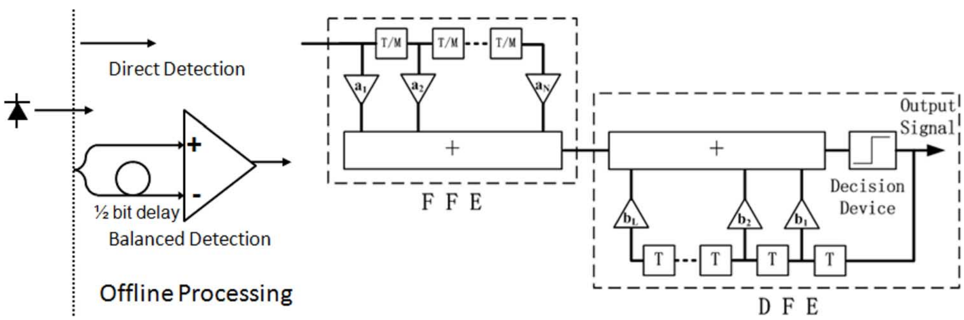
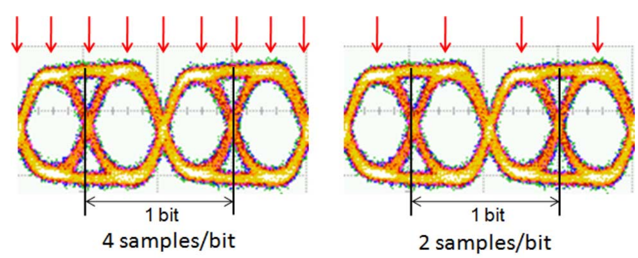


Fig. 2. Receivers for Manchester signal and the structure of FFE-DFE.

doubled through Manchester encoding. Then the electrical Manchester signal was amplified by a 22-GHz electrical amplifier to drive a quadrature-biased Mach–Zehnder modulator (MZM), which took a continuous wave input light at 1550.12 nm. The peak-to-peak amplitude $V_{\rm pp}$ of the amplified electrical Manchester signal was set to V_π (~6 V) of the MZM.

Different lengths of standard single-mode fiber (SSMF) with a dispersion coefficient of about 17 ps/nm·km at 1550 nm were utilized to study the CD tolerance of the FFE-DFE for the optical Manchester signal. In order to avoid any significant fiber nonlinearity, the power of the optical Manchester signal was kept below 0 dBm. After transmission over the SSMF, the optical signal-to-noise ratio (OSNR) of the optical signal was adjusted by injecting filtered amplified spontaneous emission (ASE) noise from an erbium-doped fiber amplifier (EDFA). The signal was then further boosted by another EDFA before being filtered by a 0.8-nm optical bandpass filter to remove the out-of-band ASE noise. The filtered signal was finally detected, via a PIN photodiode. The detected electrical signal was then sampled by a Tektronix DSA72004 digital serial analyzer, operating at 50 GS/s. For each combination of CD and OSNR values, the duration of the sampling time was 100 μs, which corresponded to more than 1 million bits of the signal. Equalization with FFE-DFE was realized by offline digital signal processing on a personal computer. For performance comparison, we also performed similar measurements using optical BD. According to Nyquist criterion for signal sampling, at least four samples for each Manchester bit were needed to fully reconstruct the waveform. Therefore, it was expected that the CD compensation capability of FFE-DFE could be fully exploited when its FFE stage took four samples from each Manchester bit (i.e., 4 samples/bit). At this sampling rate, we assumed the four samples were taken at 0, 1/4 T, 1/2 T, and 3/4 T of each symbol,



(a) (b)

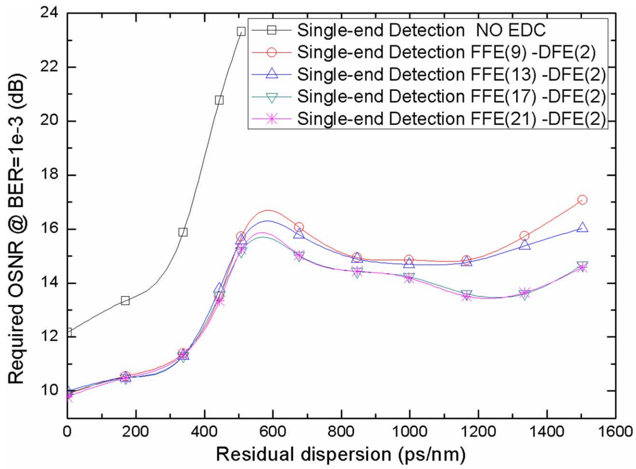
Fig. 3. Optical eye diagrams of Manchester signal and corresponding sampling schemes for equalization. (a) 4 samples/bit sampling. (b) 2 samples/bit sampling.

where T was the bit period, as shown in Fig. 3(a). We have also investigated the CD compensation performance of FFE-DFE when the sampling rate was reduced to 2 samples/bit. In this case, the samples were taken at 1/4 T and 3/4 T, as shown in Fig. 3(b). The equivalent FFE-DFEs employed were the same as the one shown in Fig. 2 with $M = 4$ (4 samples/bit) and $M = 2$ (2 samples/bit). The tap weights of the FFE-DFE were adapted with least mean square algorithm, using the first 5000 bits for training before entering decision-directed mode. After training with 5000 bits, the mean square error of the equalized samples was merely 5.43% different from optimum value, which guarantees the performance.

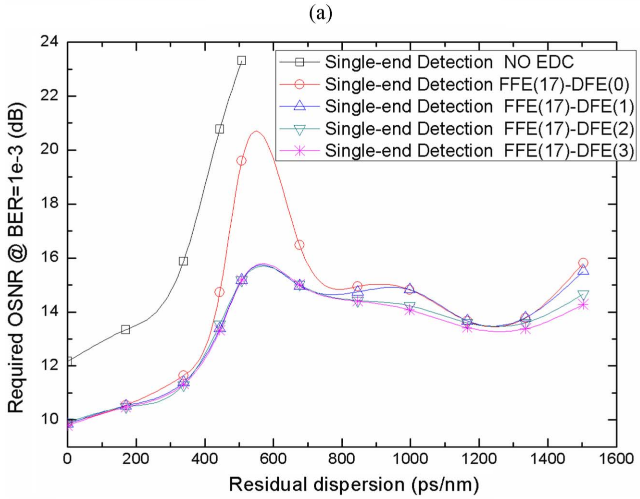
III. Results and Discussions

A. FFE-DFE at 4 samples/bit

FFE-DFEs with different number of taps were used to evaluate their CD compensation capability for the optical Manchester signals. At the sampling rate of 4 samples/bit, a minimum number of 9 FFE taps have been considered, which



(a)



(b)

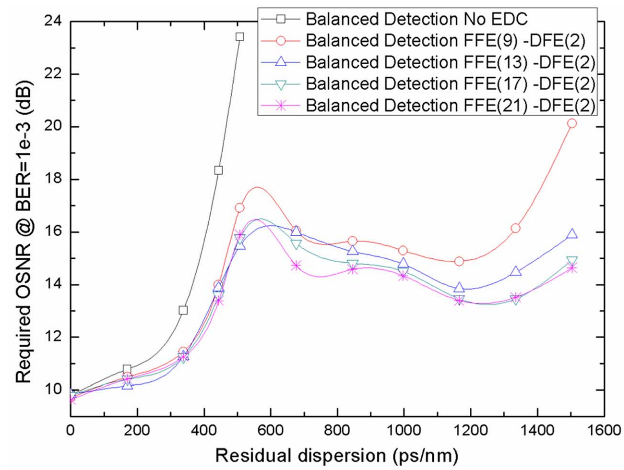
Fig. 4. Required OSNR versus residual CD for 10.709-Gb/s Manchester signal with different number of FFE/DFE taps using SD. (a) FFE with different number of taps followed by DFE(2). (b) FFE(17) followed by DFE with different number of taps.

utilized the information from prehalf and posthalf symbol for equalization. Fig. 4(a) and (b) shows the required OSNR for the 10-Gb/s optical Manchester signal to achieve a bit-error-rate (BER) of 10^{-3}, under various residual CD values when different kinds of FFE-DFEs and SD were employed. From the figure, it is shown that, without equalization, the required OSNR increased from 12.16 to 15.88 dB when the residual CD was raised from 0 to 338.06 ps/nm and the required OSNR increased drastically afterward. When FFE-DFE was applied, about 2 dB improvement in the required OSNR was observed at zero CD value. Such improvement could be attributed to the emulation of BD, via the FFE-DFE, by constraining the corresponding FFE-DFE coefficients for the first half bit and the second half bit to be of opposite numbers.

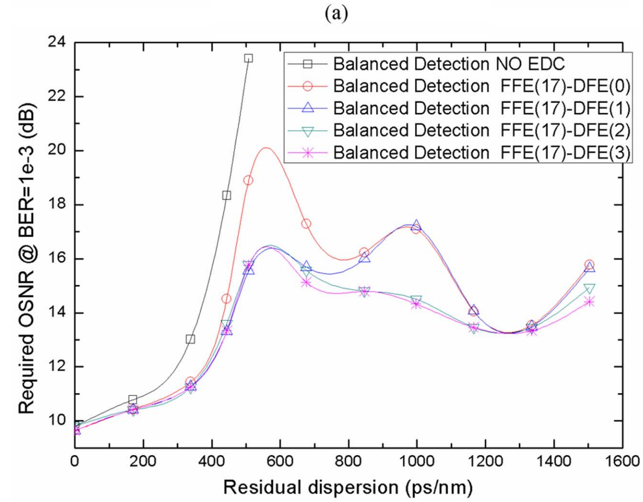
Fig. 4(a) shows the required OSNR curves when the number of DFE taps was fixed to 2. For all the FFE-DFEs with the number of FFE taps ranging from 9 to 21, the required OSNR curves first rose rapidly when the residual CD increased from 350 to 500 ps/nm, then became leveled off at around 14 dB when the residual CD continued to increase from 500 to 1533 ps/nm. At the residual CD value of 1673 ps/nm, in all cases, the measured BER was larger than 1×10^{-3}, even when the OSNR was increased to 24 dB. Thus, it was expected that the required OSNR curves would rise abruptly at the residual CD values beyond 1533 ps/nm. On the other hand, when the number of FFE taps was increased from 9 to 17, the performance of the FFE-DFE was enhanced, though any further increase in the number of taps did not give significant performance enhancement. Hence, it could be deduced that 17 taps were sufficiently optimal for the FFE stage. At a residual CD value of 1533 ps/nm, which corresponded to 90 km SSMF transmission, the required OSNR values for FFE tap number of 9, 13, 17, and 21 were 17.07, 16.02, 14.66, and 14.57 dB, respectively. With the number of FFE taps being fixed to 17, the number of DFE taps was then varied between 0 and 3, and their required OSNR curves were shown in Fig. 4(b). All the required OSNR curves coincided when the residual CD ranged from 0 to 440 ps/nm. However, they began to diverge when the transmission distance was further increased. The sudden rise in the required OSNR curve with FFE(17)-DFE(0) implied that DFE was indispensable for the CD compensation, and significant performance enhancement was observed when the number of DFE taps was increased from 0 to 3, though the performances of FFE(17)-DFE(2) and FFE(17)-DFE(3) were rather close to each other. Hence, it could be deduced that any further increase in the number of DFE taps would not give any further significant performance enhancement in CD compensation, thus FFE(17)-DFE(2) would be an optimal design for the electronic equalizer for the optical Manchester signals under SD.

In view of the typical $\sim$2 dB improvement in the required OSNR and larger tolerance to signal level fluctuation, BD has also been widely considered for Manchester signal [3], [10], [11]. Fig. 5(a) and (b) shows the required OSNR of the 10-Gb/s optical Manchester signal to achieve a BER of 10^{-3}, under various residual CD values when different kinds of FFE-DFEs and BD were employed. Fig. 5(a) shows the performance with the FFE-DFE having different number of FFE taps and fixed 2 DFE taps. At zero CD value, the FFE-DFE could no longer enhance the performance as BD has already been employed. Without equalization, the CD tolerance was still quite poor. When the FFE-DFE was applied, the required OSNR curves exhibited similar trend as those under SD, as in Fig. 4(a). Hence, it could be deduced that 17 FFE taps were optimal to guarantee the performance of FFE-DFE, under BD. From Fig. 5(b), it was shown that the performances of FFE-DFE without DFE taps or with only one DFE tap were significantly inferior to that with two DFE taps. Hence, at least two DFE taps should be used for systems using BD.

From the earlier results using SD or BD schemes, it could be concluded that there was no benefit of using BD for optical Manchester signal when FFE-DFE was used for CD compensation. In fact, adaptive filter like FFE-DFE could emulate BD by properly constraining the coefficients of the FFE taps, for instance, by setting the weights of first two taps in the FFE with opposite polarity to that for the latter two taps for each bit. The performance was satisfactory when the FFE-DFE had 17 FFE taps and two DFE taps. From our results, any further increase in the number of FFE or DFE taps would not significantly further improve the CD tolerance.



(a)



(b)

Fig. 5. Required OSNR versus residual dispersion for 10.709-Gb/s Manchester signal with different number of FFE/DFE taps using BD. (a) FFE with different number of taps followed by DFE(2). (b) FFE(17) followed by DFE with different number of taps.

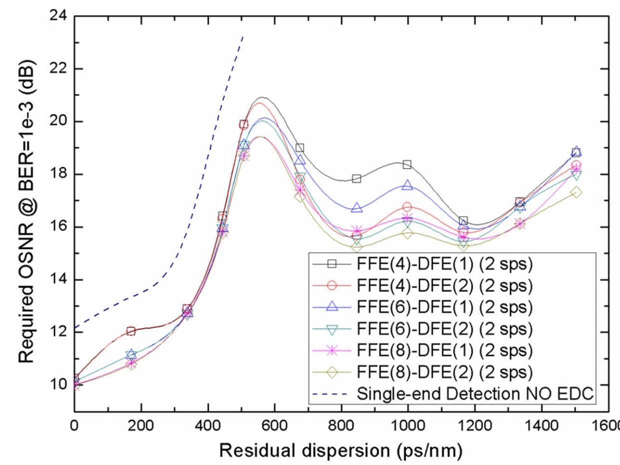


Fig. 6. Required OSNR versus residual dispersion for 10.709-Gb/s Manchester signal using single-end detector and two samples per symbol scheme with different number of FFE/DFE taps.

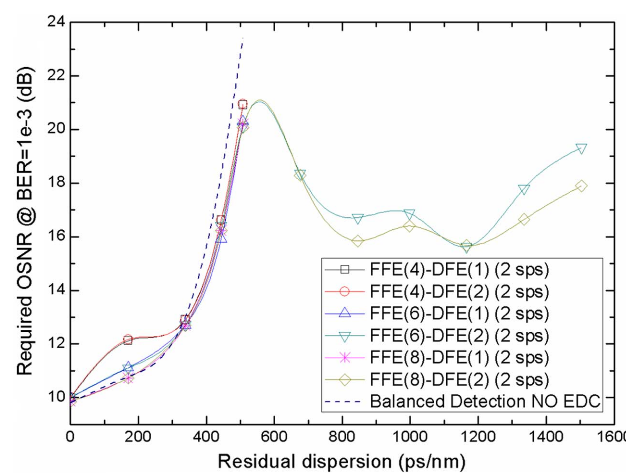


Fig. 7. Required OSNR versus residual dispersion for 10.709-Gb/s Manchester signal using balanced detector and two samples per symbol scheme with different number of FFE/DFE taps.

B. FFE-DFE at 2 samples/bit

We have also investigated the CD compensation capability of FFE-DFE when its sampling rate was reduced by half to 2 samples/bit. Similar to the case with FFE-DFE at 4 samples/bit, both SD and BD schemes were considered for FFE-DFE at 2 samples/bit. As shown in Fig. 3(b), a minimum number of four FFE taps were required to utilize samples from the prehalf and posthalf symbols. Fig. 6 depicts the required OSNR curves for the 10-Gb/s optical Manchester signal with FFE-DFE having different number of DFE taps and FFE taps. As the signal was sampled at the maximum eye opening points in the first and the second half of each bit, the 2 dB improvement in the required OSNR at zero CD could still be achieved with FFE-DFE. When the number of DFE taps was 1, increasing the number of FFE taps showed remarkable improvement in the required OSNR. Nevertheless, when the number of DFE taps was 2, increasing the number of FFE taps from 4 to 8 would still reduce the required OSNR, but the benefit was less than 2 dB. The results implied that at least two DFE taps were needed in FFE-DFE at 2 samples/bit, for optimal performance, and much fewer taps for FFE were required as compared to FFE-DFE at 4 samples/bit. Besides, when the CD value ranged from 508 to 676 ps/nm, the required OSNR was quite large, thus prohibited the use of FFE-DFE at 2 samples/bit in such transmission distance. However, the required OSNR was well maintained at around 16 dB when the residual CD was between 845 and 997 ps/nm. Therefore, FFE-DFE at 2 samples/bit offered a cost-effective solution to relax the requirement of OSNR in long-reach optical access network, which has typical transmission distances around 80 km (equivalent to a residual CD value of 1356 ps/nm). Fig. 7 depicts the results when FFE-DFE at 2 samples/bit was considered under BD. It was shown that only FFE(6)-DFE(2) and FFE(8)-DFE(2) were capable of improving the CD tolerance while BER of 10^{-3} could not be achieved using other FFE-DFE for CD values beyond 508 ps/nm. Compared with SD, BD was less robust when FFE-DFE at 2 samples/bit was used to electronically compensate the CD for optical Manchester signals.

As the 2 samples/bit scheme required sampling at the 1/4 T and 3/4 T (maximum eye opening) points, the phase error tolerance has been studied. Fig. 8 shows the relationship between the sampling phase error and the required OSNR at BER of 10^{-3}. The phase error was defined as the ratio of the sampling

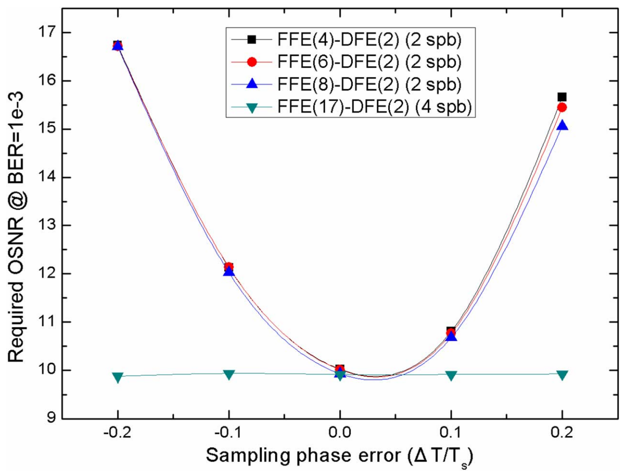


Fig. 8. Required OSNR versus sampling phase error for 2 samples/bit scheme at back to back.

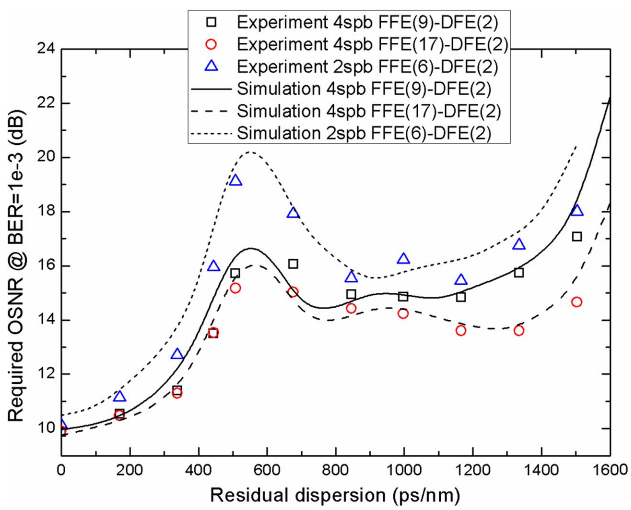


Fig. 9. Comparison of 2 samples/bit scheme and 4 samples/bit scheme for equalizer with different number of FFE taps.

time misalignment ΔT and the symbol duration T_s. To maintain good performance (< 2 dB penalty in required OSNR), the phase error should be less than 0.1. The asymmetry of the phase error induced penalty was attributed to the asymmetric rising and falling edges of our generated optical Manchester signal.

C. Discussions

The CD compensation capability of FFE-DFE has been verified by both numerical simulation and experiment. As shown in Fig. 9, using different FFE-DFEs and under either 2 samples/bit or 4 samples/bit schemes, the experimental results agreed with the numerical results very well. For most of the CD values, the increase in required OSNR of using FFE-DFE at 2 samples/bit, compared with the 4 samples/bit case, was less than 2 dB. At the CD values between 845 and 1172 ps/nm, such increase in required OSNR was less than 1 dB. However, such penalties were relatively large when the CD value was between 508 and 676 ps/nm, which prohibited the application of FFE-DFE at 2 samples/bit in this range. In general, the results confirmed that FFE-DFE at 2 samples/bit could reduce the number of FFE taps at the expense of the higher required OSNR (difference less than 2 dB). The simulated results have also showed that the required OSNR increased drastically in the presence of residual dispersion beyond 1533 ps/nm, regardless of the type of FFE-DFE and the sampling scheme utilized. This could be a fundamentally limitation caused by CD.

As shown in Fig. 9, there was a surge in the penalty of required OSNR for 10.709-Gb/s Manchester signal between CD values of 500 and 600 ps/nm. In our numerical simulation, the maximum penalty point appeared at a CD value of 580 ps/nm. Such penalty surge in required OSNR could be explained by analyzing the eye diagrams and the FFE tap coefficients, as illustrated in Fig. 10. Fig. 10(a), (b), (c), and (d) depict the simulated eye diagrams at CD values of 380, 480, 580, and 680 ps/nm, respectively. Their corresponding FFE tap coefficients are shown in Fig. 10(e), (f), (g), and (h), respectively, assuming FFE(9)-DFE(2) was adopted. The shaded areas in the eye diagrams were the eye opening areas of the transmitted symbol. The FFE utilized both the first and the second half of the symbol for equalization. Therefore, the corresponding coefficients for the samples of the first and the second half of each bit were opposite, which were indicated by the closed circles in the lower figures in Fig. 10. With the increase in the CD value, the eye opening was reduced and the eye became completely closed at the CD value of 580 ps/nm, and the FFE could hardly differentiate the two traces. This corresponded to the local maximum of the required OSNR, as in Fig. 9. However, any further increase in the CD value would lead to effective eye opening in the neighboring bits [see Fig. 10(d)], and the FFE could then differentiate the two traces again. Therefore, the CD could be better compensated. Besides, similar to Figs. 4–7, the penalty curves in required OSNR exhibited surge at moderate residual CD and this could be attributed to the noise enhancement characteristics of the equalizer, as discussed in [17].

Fig. 11 depicts the performance comparison between Manchester and NRZ-OOK formats with different number of FFE taps, via simulation. 4 samples/bit FFE(13)-DFE(2) and 2 samples/bit FFE(7)-DFE(2) were selected for Manchester signal and NRZ-OOK signal, respectively. The lower sampling rate of 2 samples/bit was sufficient for the NRZ-OOK signal, due to its narrower bandwidth. The time spans within which the samples were utilized for both types of signals were the same. As shown in Fig. 11, although the performance of the Manchester signal with FFE-DFE was still worse than that of NRZ-OOK without equalization, except the residual CD ranges between 1260 and 1417 ps/nm, the FFE-DFE did improve the dispersion tolerance of the Manchester signal significantly. For instance, at the required OSNR of 15 dB, the FFE-DFE increased the CD tolerance by about three times, while the improvement for NRZ-OOK was about 60%. Such drastic improvement for the Manchester signal would greatly enlighten its practical applications in optical access networks.

IV. Summary

The capability of CD compensation using FFE-DFE for Manchester coded signal has been studied and evaluated, under both SD and BD schemes. Two fractional spaced FFE structures at both 4 samples/bit and 2 samples/bit have been further investigated and compared. With such an electrical equalizer, the transmission distance of Manchester signal could be tripled. Our results have also showed that BD did not effectively improve the

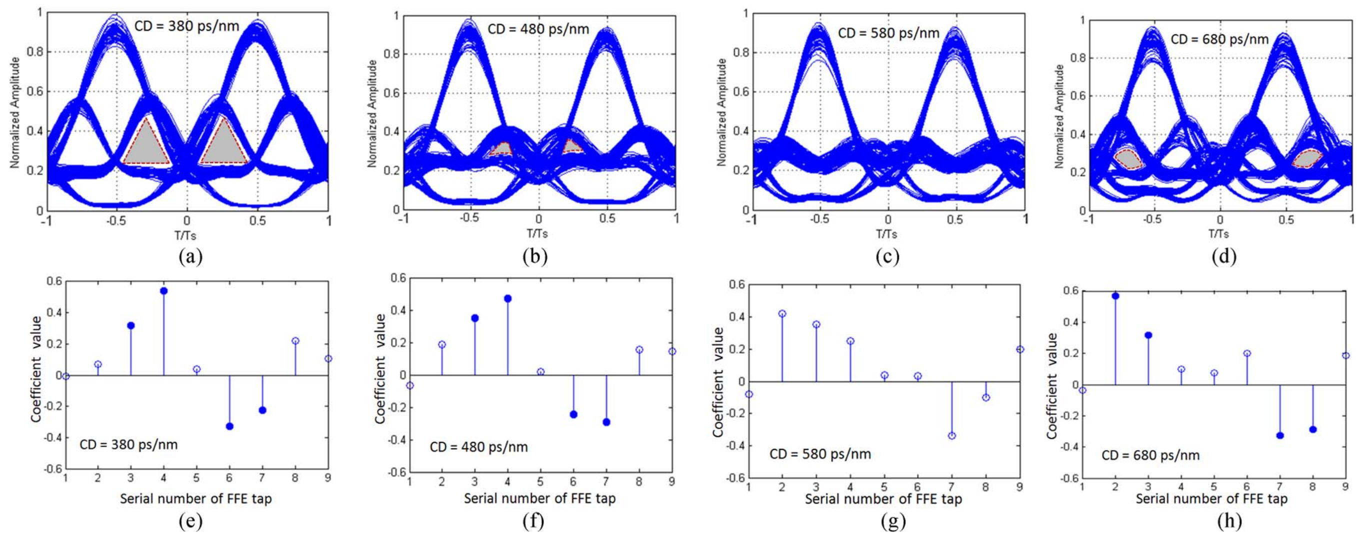


Fig. 10. Simulated eye diagrams for Manchester signal and corresponding FFE tap coefficients for FFE(9)-DFE(2) at different CD values. (a) and (e) 380 ps/nm. (b) and (f) 480 ps/nm. (c) and (g) 580 ps/nm. (d) and (h) 680 ps/nm.

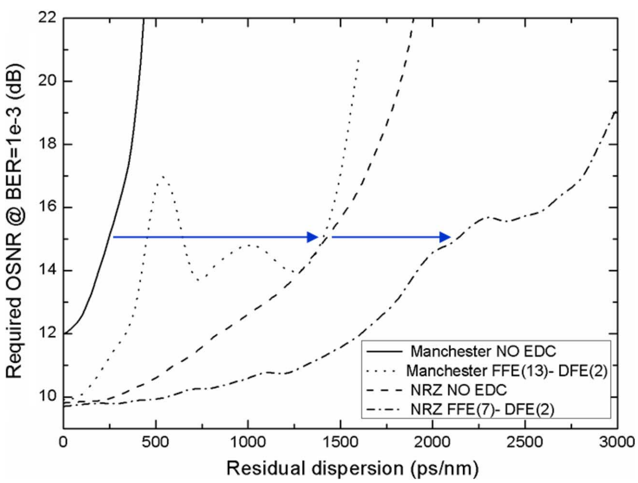


Fig. 11. Comparison of Manchester and NRZ for equalizer with different number of FFE taps.

receiver sensitivity in 4 samples/bit based equalizer and was much less robust in 2 samples/bit based equalizer. Two DFE taps were needed to ensure good CD tolerance. By taking two samples at the maximum eye opening points in the first and the second half symbol for equalization, the number of FFE taps could be remarkably reduced, at the expense of a certain penalty in required OSNR (< 2 dB), which was induced by the possible frequency overlapping due to subsampling. For applications that such required OSNR penalty is tolerable, tradeoff could be made between the CD tolerance and the number of FFE taps.

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