Frequency-Domain Equalization for Coherent Optical Single-Carrier Transmission Systems

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Frequency-Domain Equalization for Coherent Optical Transmission Systems

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Abstract: Frequency-domain equalization (FDE) has been attracting much attention for high-speed long-haul transmission over fiber-optic channels. Two FDE configurations for coherent optical transmission are presented and some applications are also described.

OCIS codes: (060.1660) Coherent communications; (060.2360) Fiber optics links and subsystems

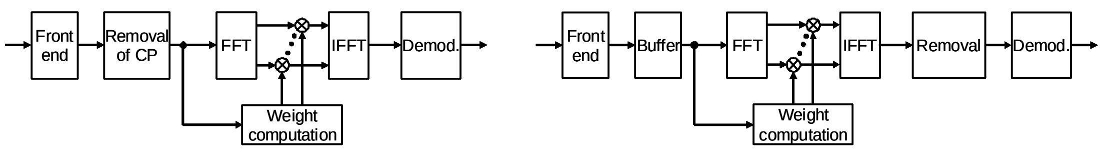
1. Introduction

For the forthcoming 100 Gbit/s/ch-class ultra-high-capacity optical transport network (OTN), various digital signal processing (DSP) techniques have been investigated to improve the transmission performance in a fiber-optic channel [1]. It was shown that the use of frequency-domain equalization (FDE) technique based on DSP can compensate the effects of chromatic dispersion (CD) and polarization mode dispersion (PMD) without dispersion compensation in coherent optical single-carrier (CO-SC) transmission [2],[3]. FDE has been proposed for the wireless channel [4],[5] and adopted in 3rd generation long-term evolution (3G-LTE) systems [6]. CO-SC-FDE improves the transmission quality with reduced the calculation complexity owing to its block-to-block operation by using fast Fourier transform (FFT). FDE is very attractive because it has much lower calculation complexity than time-domain equalization (TDE) when the equalizer has many taps [3],[7]. Although CO-OFDM transmission also has low calculation complexity because of its block-wise operation, CO-SC-FDE remains advantageous since CO-SC signals have much smaller peak-to-average-power ratio (PAPR) than CO-OFDM signals. This results in more robustness against fiber nonlinearity [8],[9].

There are two FDE configurations for CO-SC. The CP-FDE configuration [3] inserts a CP into a guard interval (GI) so that the received signal can be a circular convolution of the transmitted signal block and the channel impulse response. The other is the overlap FDE (O-FDE) configuration [10], which can eliminate inter-block interference (IBI) caused by the cyclic distortion although it does not require CP use. This paper describes the two FDE configurations and introduces some FDE applications for high-capacity long-haul transmission over optical channels.

2. Basic FDE configurations

Figs. 1(a) and (b) show simple block diagrams of CP-FDE and O-FDE, respectively. In CP-FDE, N-point FFT is applied to decompose the received signal into N frequency components and 1-tap equalization is then carried out in the frequency-domain with respect to each block. In well-known CP insertion, the last N_{cp} symbols of the FFT block are copied and inserted, exactly as in OFDM, at the beginning of the block. If CP length is longer than the maximum time delay difference of the channel impulse response, CP can avoid the IBI from the previous block. In SC-FDE transmission, unique word (UW) can be used as CP [4]. A UW of N_{cp} symbols is inserted at the end of each FFT block and the previous UW is used as the CP for the present block. Since each UW is a known symbol sequence, it can be used for not only CP but also synchronization and equalization. In O-FDE, 1-tap equalization is carried out in the frequency-domain by using FFT operation as CP-FDE. The difference from CP-FDE is that the IBI caused by the adjacent samples affects the first and last few samples due to the cyclic distortion as shown in Fig. 2 since there is no CP. Thus, the first M samples and the last M samples in the N samples are removed as shown in Fig. 3, and the remaining $M_0 = (N\text{-}2M)$ samples with a low IBI level are extracted. Finally, the obtained samples are demodulated and the transmitted data are obtained. The above process is applied to all received signals with a sliding M_0-received-signal in each FFT block as shown in Fig. 3 to obtain the entire transmitted data sequence. Fig. 4 shows the numbers of the multiplications per second for TDE and FDE operations when the sampling rate is assumed to be



(a) CP-FDE (b) O-FDE
Fig. 1 Simple block diagram of two FDE configurations.

50Gsample/s. FDE has a clear advantage over TDE in reducing DSP complexity if the number of equalization taps is large. CP-FDE can further reduce, by the factor of M_0/N, the amount of calculation complexity compared to O-FDE, but its transmission efficiency is degraded by the use of CP.

FDE requires a weight computation that involves the estimated channel transfer function. To estimate the channel transfer function, a constant amplitude zero autocorrelation (CAZAC) sequence is preferable as the pilot sequence since its magnitude is uniform across the frequency spectrum, which allows the channel transfer function to be accurately estimated. However, in high-speed optical communication systems, a binary-valued sequence is more desirable from the viewpoint of the complexity of the transmitter, e.g., DAC. In contrast, a pseudo-noise (PN) sequence is preferable as the pilot symbol sequence since smaller variations in the pilot symbol spectrum can be achieved without DAC. To improve the estimation accuracy, the delay time-domain filtering scheme is reasonable [10]. For FDE, although various weights exist, FDE based on the minimum mean square error (MMSE) criterion can provide the best compromise between noise enhancement and signal distortion compensation, and gives the best bit error rate (BER) performance [5]. Fig. 5 shows the BER performances of CO-SC with CP-FDE and O-FDE as a function of OSNR for the back-to-back and after transmission cases. It is assumed that the numbers of FFT points and UW symbols for CP-FDE and the discarded symbols for O-FDE are 512, 16 and 16, respectively. For comparison, the BER performances of differential direct detection are also plotted. It can thus be seen that CP-FDE and O-FDE offer about 2dB better BER performance than differential direct detection in the back-to-back case due to coherent detection. Furthermore, neither FDE technique exhibits performance degradation after 240 km SMF (CD of 4080 ps/nm) transmission. This result shows that both FDE methods compensate the linear effect created by CD. FDE can also compensate the effect of PMD as shown in Ref. [9]. In addition, for polarization-division multiplexing (PDM) transmission, channel equalization and signal separation can be simultaneously carried out in the frequency-domain by applying FDE in multiple-input multiple-output (MIMO) transmission over wireless channels [11].

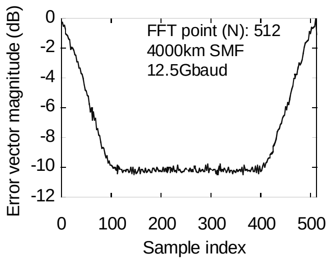


Fig. 2 IBI distribution in an FFT block.

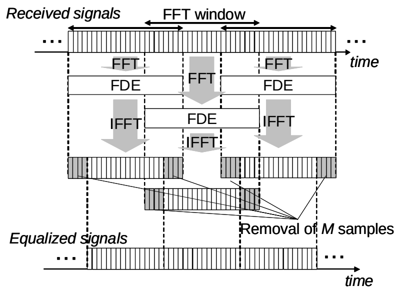


Fig. 3 O-FDE flow.

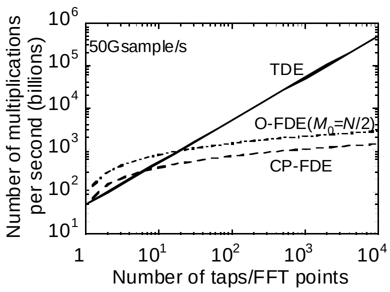


Fig. 4 Complexity comparison between TDE and FDEs.

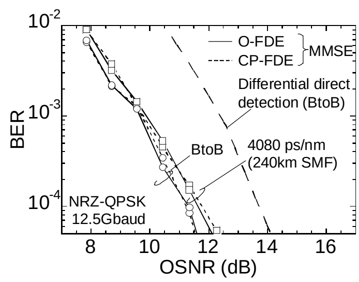


Fig. 5 BER performance comparison between CP-FDE and O-FDE.

3. Applications of FDE to the fiber-optic transmission

In wireless communications, the propagation channel comprises many distinct paths due to the many obstacles located between the transmitter and receiver, and is time variant due to the mobile's movement. By contrast, the propagation channel for fiber-optic communication principally exhibits CD and PMD, which have different characteristics. CD has very large differences in the maximum delay time due to long-haul transmission and the large number of equalization taps in fiber-optic systems is required compared to that in wireless systems. PMD requires fewer taps than CD but it makes the channel time varying. This in not a major problem since optical systems have much higher data transmission rates than wireless systems and so the time variation of optical channel is very small compared to that of wireless channel. Therefore, two-stage equalization is very suitable for fiber-optic transmission systems [12]. Fig. 6 shows the DSP block diagram of two-stage equalization. At the first stage, CD is compensated by using O-FDE, using equalization weights given in [13]; many estimation techniques have been investigated [14]. After IFFT operation in O-FDE, the first and last samples in an FFT block, whose length are longer than the maximum delay-time difference caused by CD, are removed to eliminate the IBI. At the second stage, either TDE or FDE is performed to compensate the effects of PMD and the other factors degrading performance. Both TDE and FDE provide almost the same BER performance but FDE has much lower computational complexity than TDE if the number of equalization taps is large. Additionally, MMSE weight computation based on pilot-assisted channel estimation is faster than that obtained by the least mean square (LMS) algorithm or constant modulus algorithm (CMA) despite the degradation in transmission efficiency caused by pilot insertion [15].

Fig. 7 shows the Q-factor of 25 Gbit/s single-polarization (SP)-QPSK with two-stage equalization versus transmission distance for the *N* values of 256, 512, and 1024. Both equalization stages employ O-FDE. The number of FFT points in the second O-FDE was 16. The Q-factors were 8.0, 11.4, and 11.6 dB with *N* values of 256, 512, and 1024, respectively, over 4320 km of SMF. Fig. 7 shows that two-stage overlap FDE achieves a high Q-factor that exceeds 11 dB using *N* of 512 or greater. Furthermore, it is expected that CO-SC with two-stage O-FDE is robust against actual time varying channels since the number of FFT points in the second O-FDE is significantly reduced compared to that in the first O-FDE.

Fig. 8 shows the transmission performance in an application of FDE to high-speed long-haul transmission. We experimentally measured the Q-factor dependence on transmission distance in 160 Gbit/s PDM-16QAM transmission [16]. A 16-QAM optical signal was generated by a PLC-LN hybrid modulator through optical signal synthesis and detected with the aid of two-stage equalization consisting of O-FDE with *N*=2048 at the first stage and TDE based on the CMA-MMA algorithm with 13-tap adaptive FIR filter. The Q-factor after 3123.9 km can exceed the Q-limit of 9.1dB as shown in Fig. 8 because of the powerful equalization of CD and PMD yielded by the two-stage equalization with adequate equalization tap number. In addition, two-stage equalization based on FDE can be also applied to no-guard-interval CO-OFDM [17].

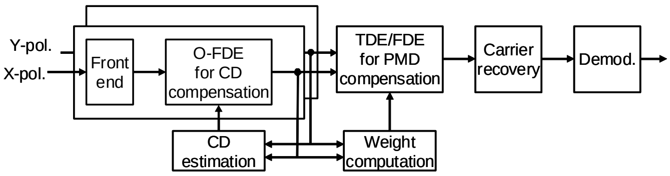


Fig. 6 DSP block diagram of two-stage equalization for the fiber-optic transmission systems.

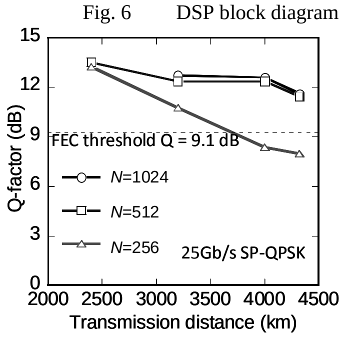


Fig. 7 Q-factor versus transmission distance with two-stage O-FDE.

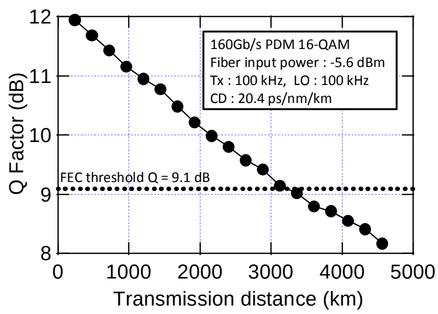


Fig. 8 The transmission performance of 160-Gb/s PDM-16QAM.

4. Conclusion

We have reviewed two FDE configurations and some applications of FDE for high-capacity long-haul transmission over optical channels. In term of computational complexity, FDE is superior to TDE although both provide the same performance in theory. Furthermore, two-stage equalization, which uses O-FDE at the first stage and TDE/FDE at the second stage (CD and PMD are compensated separately), is suitable for high-speed long-haul transmission over fiber-optic channels.

References

[1] Y. Miyamoto and S. Suzuki, IEEE Commun. Mag., pp.65-72, Mar. 2010.
[2] W. Shieh, et al., Journal of Optical Networking, vol. 7, pp. 234-255, Feb. 2008.
[3] K. Ishihara, et al., in Proc. ECOC2008, Paper We.2.E.3.
[4] D. Falconer, et al., IEEE Commun. Mag., vol. 40, no. 4, pp. 58–66, Apr. 2002.
[5] F. Adachi, et al., IEICE Trans. Commun., vol. E32-B, no.9, Sep. 2009.
[6] 3GPP, TS36.201 (V8.1.0), Nov. 2007.
[7] B. Spinnler, et al., in Proc. ECOC2008, Paper We.2.E.4.
[8] S. L. Jansen, et al., in Proc. ECOC2008, Paper Mo.3.E.3.
[9] K. Ishihara, et al., IEICE Trans. Commun., vol.E92-B, no.12, pp. 3736-3743, Dec. 2009.
[10] K. Ishihara, et al., Electron. Lett., vol. 44, no. 25, pp. 1480-1482, Dec. 2008.
[11] J. Coon, et al., IEEE Trans. Signal Process., vol. 53, no.8, pp. 3247-3256, Aug. 2005.
[12] R. Kudo, et al., J. Lightw. Technol., vol. 27, no. 16, pp. 3721-3728, Aug. 2009.
[13] G. P. Agrawal, Nonlinear Fiber Optics. San Diego, CA: Academic, 1995.
[14] M. Kuschnerov, et al., in Proc. OFC/NFOEC2010, Paper OMR5.
[15] F.N. Hauske, et al., in Proc. OFC/NFOEC2010, Paper JThA11.
[16] Kobayashi, et al., in Proc. OFC/NFOEC2010, Paper OTuD1.
[17] A. Sano, et al., J. Lightw. Technol., vol. 27, no 16, pp. 3705-3713, Aug. 2009.