Effective method for Blind Adaptive CD Compensation and Estimation in a DSP-based Coherent Optical Systems

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A blind adaptive chromatic dispersion compensation and estimation algorithm is proposed and experimentally validated. The method is based on a Frequency Domain Equalizer, a Time Domain Equalizer and an Optical Performance Monitoring in a loop configuration.

1. Introduction

Optical transmission schemes based on coherent detection and digital signal processing (DSP) of polarization division multiplexing (PDM) multilevel modulation formats are considered for next generation optical networks [1]. The main advantage of coherent receivers is to provide both amplitude and phase information of the received signal. These information are used by the DSP equalizer to invert the channel linear transfer function in order to recover the transmitted signal. Hence, the digital equalizer structure aimed at compensating for all linear channel impairments, namely chromatic dispersion (CD) and polarization mode dispersion (PMD) [2]. This is particularly true in linear propagation regime. CD compensation is usually performed by a frequency-domain equalizer (FDE) [3] dedicated to compensate the majority of accumulated CD, followed by a time-domain equalizer (TDE) [4], implemented by means of four finite impulse response (FIR) filters arranged in a butterfly configuration (B-TDE), dedicated to de-multiplex the PDM signals and compensate the PMD and a low amount of residual CD [5]. The main drawback of this compensation approach is the need of a prior knowledge of the accumulated CD to properly set the FDE taps. Recently, an Optical Performance Monitoring (OPM) algorithm for coherent optical receivers based on the elaboration of the B-TDE taps coefficients has been introduced [6][7] in order to provide fibre linear parameters information in a simple, cost- and power-effective way. However, when the value of the residual CD induces an intersymbol length that could not be compensated by the low-complexity B-TDE, the filter-tap based CD estimation is not reliable and the CD is calculated with low accuracy [6]. In this paper we propose a blind and adaptive CD compensation and estimation technique that exploits the best characteristics of both B-TDE and FDE together with an auxiliary OPM block. The proposed method aims at exploiting elements already present in the system (TDE, FDE and OPM), and can be applied to networks where the propagation distance can switch dynamically [9].

2. OPM Algorithm

Since a SMF can be seen as a two-input/two-output channel, whose frequency response is represented by a 2x2 Jones matrix, accounting for both CD and PMD [6], a two-dimensional (2-D) matched filter can achieve perfect compensation of these phase distortions (see [8] and references therein). Since an adaptive time domain 2-D fractionally-spaced feed-forward equalizer (FFE), in a B-TDE structure, implements the 2-D matched filter, the B-TDE frequency response $\mathbf{H}_{\text{B-TDE}}(f)$ is strictly related to the inverse channel frequency response. $\mathbf{H}_{\text{B -TDE}}(f)$ can be written as the product of a polarization independent linear function with quadratic phase related to the CD and a frequency dependent unitary matrix representing the line PMD. The polarization independent function is expressed by:

$$\tilde{A}(f) = e^{-i\tilde{\varphi}} = e^{\left(i\cdot angle\left(\sqrt{\det\left(\boldsymbol{H}_{B\_TDE}^{-1}\right)}\right)\right)} \qquad (1)$$

Hence, we can estimate the channel CD applying a second derivative of the quadratic phase of the determinant of $\mathbf{H}_{\text{B-TDE}}(f)$:

$$\tilde{D} = \langle -\frac{2\pi c}{\lambda^2}\frac{\partial^2\tilde{\varphi}}{\partial\omega^2}\rangle \text{ [ps/nm]} \qquad (2),$$

where ⟨·⟩ indicates averaging over the signal bandwidth.

The OPM performances were tested by numerical simulations, adding a known value of CD to the line and then evaluating it with the OPM algorithm. The considered modulation format was 112 Gbit/s polarization multiplexed quadrature phase shift keying (PM-QPSK). After reaching the convergence of the B-TDE, its taps configuration was moved to the OPM algorithm, which performed the CD estimation. In Fig. 1 we report the estimated CD values ($\tilde{D}$) vs. the uncompensated D using B-TDE's having different number of taps.

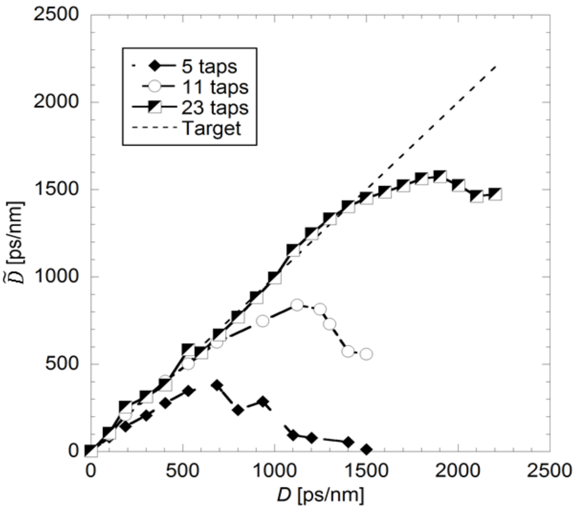

Fig. 1: OPM estimated CD ($\tilde{D}$) vs. D value. 5 taps (diamonds), 11 taps (circles) and 23 taps (black/white squares)

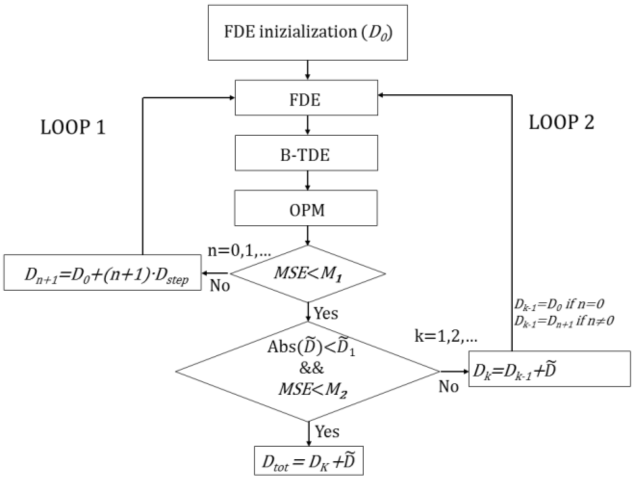

Fig. 2: Block diagram of the process flow for the proposed solution (k=K in the last iteration of Loop 2).

The B-TDE with a high number of taps (23) provides a good CD estimation up to a value of 1500 ps/nm with an error below 50 ps/nm (3.3%). Increasing D up to 2000 ps/nm the error reaches the value of 476 ps/nm (24%). Decreasing the number of taps to 11, if D = 680 ps/nm we obtained an error of 60 ps/nm (8.8%) and an error of 190 ps/nm for D = 936 ps/nm (20%). We also tested the OPM performance using a B-TDE with a minimum number of taps (5). In this case we obtained an estimation error of 180 ps/nm for D = 530 ps/nm (34%). The error increases up to 650 ps/nm for D = 936 ps/nm (70%). For higher values of uncompensated D the B-TDE does not converge and the $\tilde{D}$ value estimated is unreliable.

3. Loop Operation Principle

We propose a solution to jointly estimate and compensate CD, still exploiting the OPM even in case of long-haul link with unknown and uncompensated CD. The proposed solution exploits a FDE, a low complexity B-TDE with a limited number of taps and an OPM. It allows to obtain at the same time a precise setting of the FDE together with a good CD estimation with a blind approach. The concept is to insert the FDE-based CD compensation block, a low complexity B-TDE and the OPM in a loop configuration. In this loop, the CD value estimated by the OPM provides a feedback to the FDE. In Fig. 2 the block diagram of the process flow of the proposed solution is presented. The proposed solution is composed by two loops: Loop 1 is used to coarsely set the FDE thus allowing the B-TDE and OPM to provide a reliable value of $\widetilde{D}$, while Loop 2 performs a fine tuning of the FDE exploiting the $\widetilde{D}$ value estimated by the OPM. At each iteration of Loop 1 the mean square error (MSE) provided by the B-TDE value is compared to a threshold M_1 in order to decide if the convergence is reached so that Loop 2 could start. In Loop 2 the OPM estimates the dispersion that is left uncompensated by the FDE; this value is then passed to the FDE whose dispersion is changed, accordingly. This procedure allows to maximize the amount of CD compensated by the FDE and minimize the amount of CD compensated by the B-TDE.

In the following we report a detailed description of the process flow showed in Fig. 2. The FDE is initialized to $D_0 = 0$ ps/nm for a blind approach. After this initialization, FDE, B-TDE and OPM are applied; then the MSE value of the B-TDE is compared to a threshold (M_1). If the MSE is higher than M_1, the estimated $\widetilde{D}$ value is considered not reliable. In this case, a fixed amount of CD (D_{step}) is added to D_0 and the FDE is initialized to this new value. Then again the FDE, the B-TDE and the OPM are applied (Loop 1 in Fig. 2). Loop 1 is iterated until MSE < M_1. As soon as this condition is fulfilled, a second check on the MSE and on $\widetilde{D}$ is performed. If one of the two values is above the corresponding threshold (M_2 and $\widetilde{D}_1$), the iterative procedure enters Loop 2 and $\widetilde{D}$ is added algebraically to the value previously set in the FDE. Loop 2 terminates only when both the conditions ($|\widetilde{D}|<\widetilde{D}_1$ and MSE<M_2) are met and the algorithm stops. In this condition the B-TDE compensates only a minimum intersimbol interference (ISI) quantity defined by the residual D, the PMD and the filtering effect. The total CD compensated by the algorithm is the sum of the CD compensated by the FDE (D_M) and the CD compensated by the B-TDE and estimated by the OPM in the last iteration ($\widetilde{D}$). The parameters (threshold values and D_{step}) of the proposed algorithm are critical and must be properly chosen considering the characteristics of the system (bit-rate and modulation format).

4. Experimental Validation

We experimentally tested the proposed technique in a 112 Gbit/s PM-QPSK coherent test bed. The optical signal propagated along a recirculating loop including a 40 km Z-PLUS Fiber® span (nominal dispersion parameter equal to 20.4 ps/nm/km). The launched power was +2 dBm. We set the loop so that the signal propagated in a range from 0 to 1000 km with a corresponding CD value from 0 to 20400 ps/nm. No optical compensating fibre was used. The dependence of the compensated and estimated CD value on the number of iterations, both in Loop 1 and Loop 2, is reported in Fig. 3, for 5, 11 and 23 B-TDE taps. We considered four different propagation lengths: 200 km (dots), 520 km (squares), 760 km (diamonds) and 1000 km (triangles), corresponding to 4080, 10608, 15504 and 20400 ps/nm of nominal uncompensated D, respectively. As described before, the iterations in Loop 1 give a fixed linear D increment of 1000 ps/nm and they are represented in Fig. 3 by the points on the straight line. The number of iterations in Loop 1 depends on D_0, D_{step} and M_1. On the other hand the number of iterations in Loop 2 is defined by the number of B-TDE taps, by $\widetilde{D}_1$ and M_2. In our case the iterations in Loop 2 range between 1 (23 taps) and 7 (5 taps). We chose 5 taps as a reference, in order to demonstrate the robustness of the loop algorithm even with a very low number of taps. In a realistic case, a higher number must be considered, in order to take into account any other kind of impairments such as low-pass filtering, frequency offset, phase noise, PMD. Overall the maximum estimation error obtained in this experiment was 50 ps/nm.

5. Conclusion

We analysed the issues related to CD compensation and estimation in a DSP based coherent optical system. Using only a B-TDE, a high number of taps is needed to obtain a good accuracy of CD estimation by the OPM. We proposed a solution for jointly CD estimation and compensation in uncompensated links. This method does not require any prior knowledge of the link dispersion neither the use any training sequence, but it only exploits resources already present in the system (FDE, B-TDE, and OPM), arranging them in loop configuration, with no increase in the complexity of the equalizers. We experimentally demonstrated the validity of the proposed solution for a maximum CD value of 20400 ps/nm. Finally, we outline that this method can be used in any DSP-based coherent system employing an FDE followed by a B-TDE, regardless the modulation format and the bit-rate.

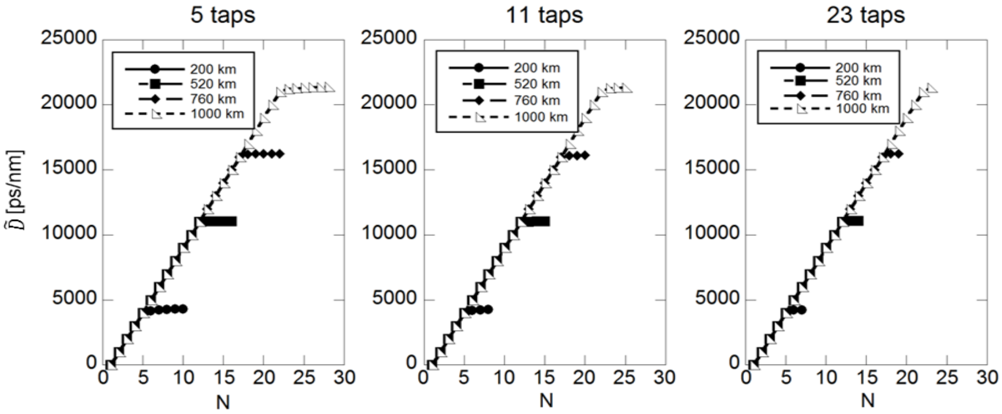

Fig. 3: $\boldsymbol{\tilde{D}}$ vs. iterations number N.

Bibliography

[1] M.G. Taylor, “Coherent detection method using DSP for demodulation of signal and subsequent equalization of propagation impairments”,
IEEE Photon. Technol. Lett., vol. 16, no. 2, pp. 674-676, Feb. 2004.

[2] S.J. Savory, “Digital filters for coherent optical receivers”, Optics Express, vol. 16, no. 2, pp. 804-817, Jan. 2008.

[3] F. Hauske, C. Xie, Z. Zhang, C. Li, L. Li and Q. Xiong, “Frequency domain chromatic dispersion estimation”, in Proc. OFC 2010, San Diego, CA, Paper JThA11.

[4] S. J. Savory, G. Gavioli, R. I. Killey and P. Bayvel, “Digital filters for coherent optical receivers”, Optics Express, vol. 15, no. 5, pp. 2120-2126, 2007.

[4] E. Ip and J.M. Kahn, “Digital Equalization of Chromatic Dispersion and Polarization Mode Dispersion”, J. Lightw. Technol., vol. 25, no. 8, pp.2033-2043, Aug. 2007.

[5] G. Colavolpe, T. Foggi and G. Prati, “Stop-and-Go Algorithm for Blind Equalization in QAM Single-Carrier Coherent Optical Systems”, IEEE Photon. Technol. Lett., vol. 22, no. 24, pp.1838-1840, Dec. 2010.

[6] T. Xu, G. Jacobsen, S. Popov, J. Li, E. Vanin, K.Wang, A. T. Friberg and Y. Zhang, “Chromatic dispersion compensation in coherent transmission system using digital filters”, Opt. Express, vol. 18, no. 15, pp. 16243-16257, July 2010.

[7] F. N. Hauske , M. Kuschnerov, B. Spinnler and B. Lankl, “Optical Performance Monitoring in Digital Coherent Receivers”, J. Lightw. Technol., vol. 27, no. 16, pp. 3623-3631, Aug. 2009.

[8] G. Colavolpe, T. Foggi, E. Forestieri and G. Prati, “Robust Multilevel Coherent Optical Systems With Linear Processing at the Receiver”, J. Lightw. Technol., vol.27, no.13, pp.2357-2369, July, 2009.

[9] R. A. Soriano, F. N. Hauske, N. G. Gonzalez, Z. Zhang, Y. Ye, I. T. Monroy “Chromatic Dispersion Estimation in Digital Coherent Receivers”, J. Lightw. Technol., vol. 29, no. 11, pp. 1627-1637, June 2011