Nonlinear Effects Compensation Analysis for Dual Polarization 16QAM Optical Coherent Systems

Victor E. S. Parahyba[1*], Eduardo S. Rosa[1] , Júlio C. M. Diniz[1], Vitor B. Ribeiro[1] and Júlio C. R. F. Oliveira[1]

(*)victorp@cpqd.com.br. 1- CPqD Foundation

Abstract — **High order modulation nonlinear effects has been appointed as the main limitation in coherent optical fiber transmission. Digital back-propagation algorithms are one of the current studied methods to cope with such impairment and extend the systems maximum reach. In this article, we analyzed the digital back-propagation performance in a 224 Gb/s dual polarization 16QAM optical coherent system. It was observed a 35% increase in maximum reached distance and an OSNR gain of 2.6 dB. In order to reduce the huge required computational complexity, an modified back-propagation algorithm is analyzed.**

Keywords — Nonlinear Effects Compensation, Dual Polarization, 16QAM, Digital signal processing, Optical Coherent Systems

I. INTRODUCTION

The growing data traffic on telecommunication systems, pushed by broadband internet applications, has made a significant impact on all kinds of communication networks. In order to comply this increasing demand, the bit rate per channel increased from 2.5 Gb/s to 40 Gb/s within ten years, and now 112 Gb/s systems start being deployed. At the same time, in order to fit more capacity into the Wavelength Division Multiplexing (WDM) spectral grid, the optical channel spacing was reduced from 100 to 50 GHz, creating denser optical systems. Due to this new scenario, it is imperative to replace the traditional On-Off Keying (OOK) modulation, present in the vast majority of deployed optical systems, by modulation formats with higher spectral efficiency. In this way, there is intensive research on multilevel modulation formats, like QPSK and QAM, using Polarization Division Multiplexing (PDM) in ultra-long-haul optical transmission systems. PDM-QSPK has been proposed as the standard modulation format for 112 Gb/s optical systems [1]. Such sophisticated transmission scheme requires a coherent receiver structure that preserves all the information of optical field (amplitude, phase and polarization), what can be explored by digital signal processing (DSP) techniques to compensate most of transmission impairments [2].

Recent advances in digital electronics enabled DSP algorithms utilization for digital compensation of various transmission impairments leading to some major achievements in distance and channel capacity [3]. After the efforts made to compensate major linear system impairments such as polarization mode dispersion (PMD) [4] and chromatic dispersion (CD) [5], the next limit in ultra-long-haul transmission are the nonlinear effects imposed by the optical fiber.

Digital Back-propagation (DBP) algorithm has become a prominent nonlinear impairment compensation method [6],[7]. DBP implementation consists on solving the reverse nonlinear Schrödinger propagation equation. However, computational complexity of DBP makes it currently unfeasible, so much effort are being made to simplify the DBP algorithm [8],[9].

In this paper, we investigate trough numerical simulation a modified DBP algorithm based on the correlation of signal power in neighboring symbols presented in [10], the Correlated Back-propagation (CBP) algorithm, in the context of a single channel transmission of 224 Gb/s PDM-16QAM over standard single-mode optical fiber (SMF). Linear equalization, DBP and CBP are compared in terms of OSNR penalty, maximum reached distance and computational complexity.

II. OPTICAL SYSTEM MODEL

The nonlinear Schrödinger equation (NLSE) describes the deterministic effects of optical fiber propagation of a single channel and single polarization signal [11]. For dual-polarization signals a pair of NLSE can be coupled in a so called Manakov system:

$$\frac{\partial E_{(x,y)}}{\partial z} = \frac{\alpha}{2} E_{(x,y)} + \frac{j\beta_2}{2}\frac{\partial^2 E_{(x,y)}}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 E_{(x,y)}}{\partial t^3} + j\gamma\left(\left|E_{(x,y)}\right|^2 + \left|E_{(y,x)}\right|^2\right)E_{(x,y)} \quad (1)$$

where $E_{(x,y)}$ is the electric field of a signal propagating in a given polarization, $E_{(y,x)}$ is the electric field of a signal propagating in an orthogonal polarization, α is the loss coefficient and describes fiber attenuation, β_2 and β_3 are related to CD and γ is the nonlinear parameter. Usually the CD effect is measured by dispersion parameter D and dispersion slope S, related to β_2 and β_3 by:

$$D = -\frac{2\pi c}{\lambda^2}\beta_2 \quad (2)$$

$$S = \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 + \frac{4\pi c}{\lambda^3}\beta_2 \quad (3)$$

where λ is the carrier wavelength and c is the speed of light. In many optical systems, especially those which employs Standard Single Mode Fibers (SSMF), the dispersion parameter is much higher than dispersion slope, and then slope impact is neglected [5]. Usually CD is the dominant linear effect in fiber propagation, and may cause severe inter-symbol interference. The last term of equation (1) describes intra-channel nonlinear effects, including non-coherent terms, responsible for Self Phase Modulation (SPM) and Intra-Channel Cross Phase Modulation (IXPM), and coherent terms responsible for Intra-Channel Four Wave Mixing (IFWM). SPM and IXPM are the dominant intra-channel nonlinear effects, and cause phase rotation in the signal, dependent of the instantaneous signal power, for SPM, and adjacent pulse power, for IXMP, including both polarizations. The combined effect of SPM and CD lead to a complex interaction that cause both phase and amplitude distortions in the signal [12].

As nonlinear effects contribution depends on the sum of instantaneous signal power on both polarizations, $\left|E_{(x,y)}\right|^2 + \left|E_{(y,x)}\right|^2$, a common measure to avoid nonlinearities is to keep low launch powers and then consider a linear propagation model. However, it limits the maximum Optical Signal-to-Noise Ratio (OSNR) and therefore the system performance at large distances. The launch power follow a tradeoff between nonlinear effects and OSNR limitation, which leads to an optimal value refereed as Nonlinear Threshold (NLT) [13].

Another fiber effect not considered in NLSE is Polarization Mode Dispersion (PMD). In addition to induce pulse broadening and Inter-symbol interference, PMD also causes severe polarization crosstalk if a dual polarization signal is transmitted. Optical linear filtering is also present in most systems, as well electric low pass filtering due bandwidth constraints of transmitter and receiver electronics. Multiplicative Phase Noise (PN) and additive Amplifier Spontaneous Emission (ASE) are the main noise sources.

III. COHERENT SYSTEM AND DIGITAL SIGNAL PROCESSING

In a polarization multiplexed system, the incoming signal is split into two orthogonal polarization components. Since the received signal has an arbitrary state of polarization caused by PMD, those components represents an unknown mixture of the transmitted data. Each component is combined with an orthogonal polarization of a free running local oscillator signal in an electrical-optical 90º hybrid with two pairs of balanced photodetectors. The electrical outputs of each optical hybrid carry the in-phase and quadrature information of the received polarization. After this, the signals pass through an anti-aliasing filter, and then, they are sampled by high speed analog to digital converters (ADC). Current ADC technologies allow sampling rates around 56 GS/s with 8 bits resolution. Since 224 Gb/s PM-16QAM systems have a 28 GBd symbol rate, it is possible to achieve up to two samples per symbol with commercial ADCs [14].

At this point, a set of digital processing techniques need to be employed to recover the transmitted data from these sampled received signals. The whole processing is divided in subsystems, as depicted in Fig. 1.

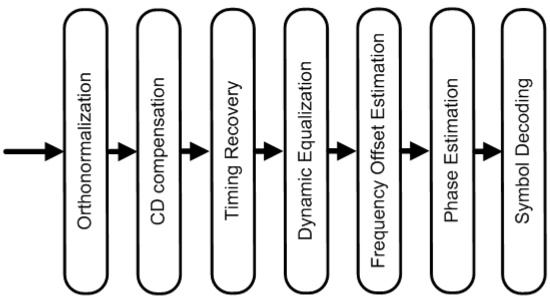


Fig. 1. - Digital signal processing for coherent systems.

The first step is the orthonormalization procedure, which aims to compensate inaccuracies in the optical hybrid that can lead to crosstalk between in-phase and quadrature components on each received polarization. Next, the static equalization subsystem aims to compensate deterministic and parametric impairments imposed by the optical fiber. Usually, a linear propagation model is assumed, and CD becomes the only deterministic propagation effect. Assuming that link length and mean dispersion parameter are known at the receiver, one can perform CD equalization using a linear filter with impulse response given by Equation (1) but with opposite signs of dispersion parameters, and neglecting the nonlinear term. This filter can be implemented in a Time-Domain Equalizer (TDE) [15] or in a Frequency-Domain Equalizer (FDE) [5], being the last approach preferred by requiring less computational effort for dispersions higher than few hundred ps/nm, even considering additional FFT and IFFT operations. The filter coefficients for a CD frequency domain equalizer are given by:

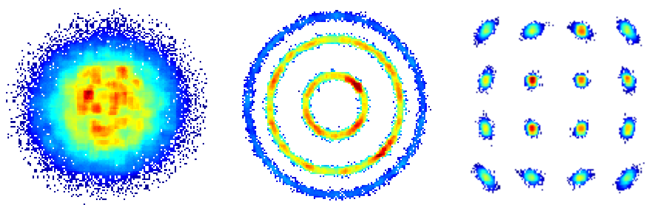
$$H(\omega, z) = \exp\left[-jz\left(\frac{\beta_2}{2}\omega^2 + \frac{\beta_3}{6}\omega^3\right)\right] \quad (4)$$

where z is the distance at which the chromatic dispersion acts and ω is the frequency vector whose center corresponds to the nominal frequency of a CD FDE.

Following CD equalization, the signal is proper for timing recovery, which aims to correct the time difference between symbol period and ADC sampling time. This procedure involves time error estimation, evaluated by criteria like Gardner algorithm [16], and signal interpolation.

After this, it is performed the dynamic equalization, which purpose is to cope with time variant and non-deterministic linear impairments, especially those related with PMD, and other linear effects not included in static equalization, like optical and electrical filtering [4]. The most common approach to perform dynamic equalization is use a adaptive time domain 2x2 MIMO (Multiple-Input-Multiple-Output) Finite Impulse Response (FIR) filter. Some variation of Constant Modulus Algorithm (CMA), Multi Moduli Algorithm (MMA) or Radius Directed Equalizer (RDE) are some options to update the equalizer for QAM signals [15].

After equalization it is necessary to perform digital carrier recovery, since the receiver usually employs an intradyne structure [17]. The first step to carrier recovery is Frequency Offset Estimation and Compensation, to identify and fix frequency mismatches between transmission and local oscillator lasers, that can achieve up to 5 GHz for commercial DFB lasers. The final step is Phase Estimation and Compensation, to compensate phase noise from transmission and local oscillator lasers. After phase estimation the recovered symbols can be decided and decoded. Fig. 2. shows the signal for one polarization at some steps of digital processing.



(a) (b) (c)

Fig. 2. - Signal as it was received(a), after dynamic equalization (b) and after phase estimation (c)

IV. NONLINEAR EFFECTS EQUALIZATION

PDM-16QAM signals require relative high OSNR to achieve a Bit Error Rate (BER) below Forward Error Correction (FEC) codes limit compared to simpler modulation formats **Erro! Fonte de referência não encontrada.**. Higher OSNR could be obtained by launching a higher optical power, however the NLT for 16QAM in standard fibers is usually very low. To reach longer distances, it is necessary to compensate nonlinear effects in fiber transmission.

Many different approaches has been evaluated to cope with nonlinear effects in optical systems, including constellation design [19], nonlinear adaptive equalizers [20], transmitter pre-distortion [21], maximum likelihood sequence estimation [22], and optical or electronic phase conjugation [23]. However, the most studied method for coherent systems is the digital back-propagation algorithm, which involves consider the nonlinear term of NLSE to design a digital static equalizer at the receiver, compensating SPM and CD at the same time. In a similar way used for CD compensation in the linear regime, this equalizer is found by solving equation (1) using α, β_2, β_3 and γ from optical link, but with opposite signs. Unfortunately, the NLSE do not have a closed analytical solution, but can be numerically solved using a non-interactive asymmetric Split-Step Fourier Method (SSFM) [12]. To do so, we have to split equation (1) in a linear and a nonlinear inverse components:

$$\frac{\partial E_{(x,y)}}{\partial z} = -\left(\frac{\alpha}{2}E_{(x,y)} + \frac{j\beta_2}{2}\frac{\partial^2 E_{(x,y)}}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 E_{(x,y)}}{\partial t^3}\right) \quad (5)$$

$$\frac{\partial E_{(x,y)}}{\partial z} = -j\gamma\left(\left|E_{(x,y)}\right|^2 + \left|E_{(y,x)}\right|^2\right)E_{(x,y)} \quad (6)$$

Instead of solve entire NLSE, we solve the linear term, given by (5), and then the nonlinear term, given by (6). This procedure can only be applied if the impact of linear distortion do not affect nonlinear operation and vice-versa, which do not hold for an entire optical link. Instead, we have to split the link into sections small enough to apply (5) and (6) separately, and solve them in sequence. The solution for the linear component is already given in frequency domain in equation (4). The solution for the nonlinear component is given in time domain by:

$$E_{x,y}(t, z+h) = E_{x,y}(t,z)\exp\left(-j\gamma h_{eff}P(t,z)\right) \quad (7)$$

$$P(t,z) = \left|E_{x,y}(t,z)\right|^2 + \left|E_{y,x}(t,z)\right|^2 \quad (8)$$

where h is the step size, the considered fiber section length, and h_{eff} is a fraction of h that corresponds to the length of fiber under the influence of SPM. The equalizer structure consists in repeated steps of linear and nonlinear operations. As linear equalization is performed in frequency domain, while nonlinear equalization is performed in time domain, each step includes direct and inverse Fourier transformations (FFT and IFFT). Fig. 3. shows a schematic of the BP equalizer.

This model has some simplifications that contribute to a penalty in relation to an ideal model. The algorithm assumes that all transmission effects are well known and are invertible. In this context, the method should be able to compensate all the linear and nonlinear effects of the optical transmission. However, insertion of terms describing frequency offset, optical filters and others would make the model extremely complex and computationally expensive. Some impairments that are stochastic by nature, such as PMD, would not be well represented. Therefore, although it is not a perfect system compensation, the only subsystem that is integrated with nonlinearity is CD equalization, with all others being treated separately.

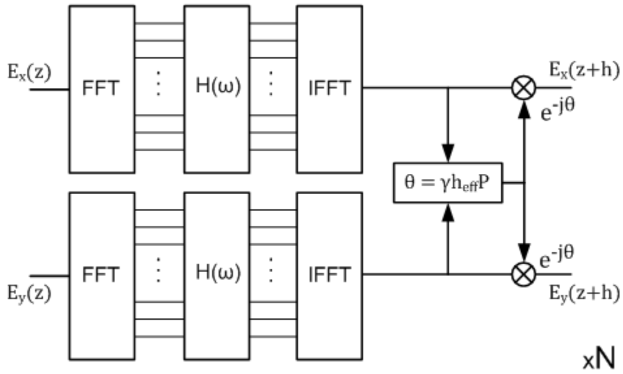


Fig. 3. - Step of back-propagation algorithm with linear equalization in frequency domain and nonlinear equalization in time domain.

BP computational complexity scales linearly with the number of steps, reaching unrealistic values for current practical applications [10]. In the other hand, we cannot reduce the number of steps without penalize equalization performance. For a classical BP, one step per link span is usually taken as a complexity lower bound. In [10], a modified Correlated Back Propagation (CBP) was proposed, including the contribution of the first order IXMP to nonlinear equalization by considering the neighbor symbols:

$$P(t,z) = \sum_{n=-T/2}^{n=T/2} b_n\left(\left|E_{x,y}(t+n,z)\right|^2 + \left|E_{y,x}(t+n,z)\right|^2\right) \quad (9)$$

where T is the number of symbols considered and b_n is a weighting coefficient. Although that algorithm has a slightly higher complexity per step, it requires less steps to achieve the same equalization accuracy, then the overall complexity is reduced.

V. SIMULATION SETUP

Fig. 4. depicts the transmitter, optical link and receiver structure for a PDM-16QAM system at 224 Gb/s. Forward transmission is simulated in Optiwave, where the signal is automatically up-sampled to 32 samples per symbol to properly account for nonlinear effects.

The transmitter consists of a laser centered at 193.4 THz with 500 kHz linewidth, followed by a polarization beam splitter (PBS). Each polarization component pass through a QAM modulator driven by four 28 Gb/s sequence generators and then combined again by a polarization beam combines (PBC) and sent over the transmission link. The transmitted sequences are a pseudo random pattern with 2^{30} bits.

The link consists of a 100 km per loop of standard single mode fiber (SSMF) and an erbium doped fiber amplifier (EDFA) with a noise figure of 5 dB which is adjusted to fully compensate the attenuation of the channel. The fiber has attenuation (α) of 0.2 dB/km, dispersion (D) of 16.75 ps/nm/km, and a nonlinearity coefficient (γ) of 1.5 W/km; for simplicity, we do not consider third-order dispersion effects (slope). Self phase modulation nonlinear effects were included according to the Schrödinger equation and polarization mode dispersion effects are considered with a PMD coefficient of 0.1 $ps/\sqrt{km}$. The "coarse-step method" is used to simulate the PMD effects [24].

After fiber transmission, the received signal was pre-amplified (constant power of 0 dBm), filtered using a 200 GHz bandwidth 4th order Gaussian optical band-pass filter, and passed through a PBS. Each polarization component was then coherently detected by an electrical-optical hybrid (EO Hybrid) with 2º phase shift error and two pairs of balanced photodiodes. The local oscillator laser has a linewidth of 500 kHz and a frequency offset of 2 GHz from the transmitter laser frequency. The four electric analogical signals are filtered using a 22 GHz bandwidth 1st order low pass gaussian filter to simulate the effect associated with a real receiver and by a 30 GHz bandwidth 4th order low pass gaussian filter to simulate the filtering effect of an oscilloscope. Finally, the data is resampled to 2 samples per symbol.

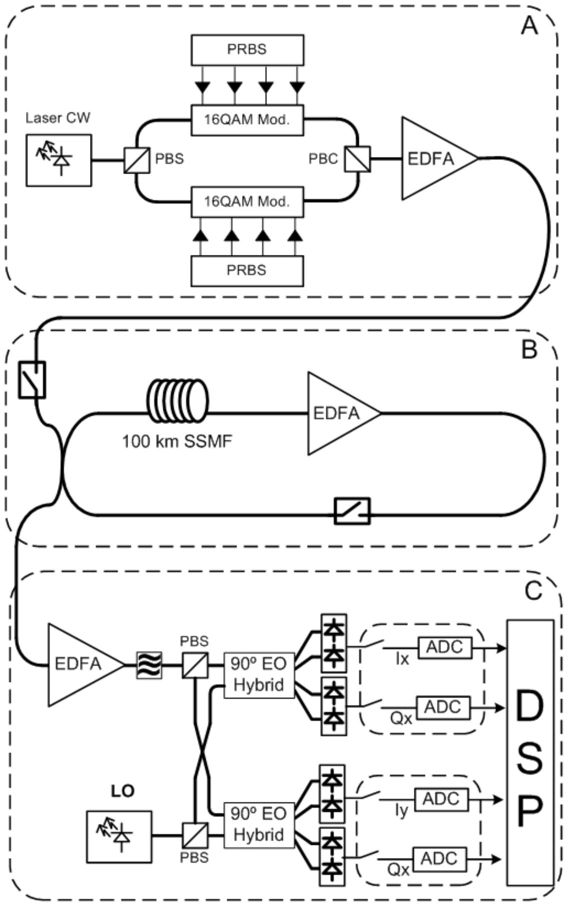


Fig. 4. Simulation system schematic: (A) transmitter, (B) recirculation loop, (C) receiver

Digital post-processing is performed entirely in MATLAB and includes an orthonormalization algorithm to compensate front-end imperfections and Gardner algorithm to timing and clock recovery. Dynamic equalizer is updated with conventional CMA for pre-convergence and then refined using RDE. Frequency offset estimation employs a frequency domain approach and finally a decision-directed algorithm performs phase estimation and correction. Static equalization, applied after orthonormalization procedure, uses a conventional CD FDE for linear equalization, or the presented back-propagation algorithms for joint compensation of nonlinear effects and CD.

VI. SIMULATION RESULTS AND DISCUSSION

Fig. 5. shows the estimated BER when using linear compensation only and one step-per-span digital back-propagation for a 800 km transmission. In both cases we assume that α, β_2, β_3 and γ are known at the receiver. Each BP step has a h of 100km and a h_{eff} of 40km. As we should expect, the gain using DBP increases with higher launch powers because of the impact of the nonlinear effects. Launch powers above 2 dBm present an increasing penalty, indicating that the implemented algorithm does not fully compensates the nonlinear effects, possibly IXPM of high orders, IFWM and noise-signal nonlinear interactions. The NLT is increased from 0dBm to 2 dBm by the use of the DBP which can be translated in a better OSNR performance.

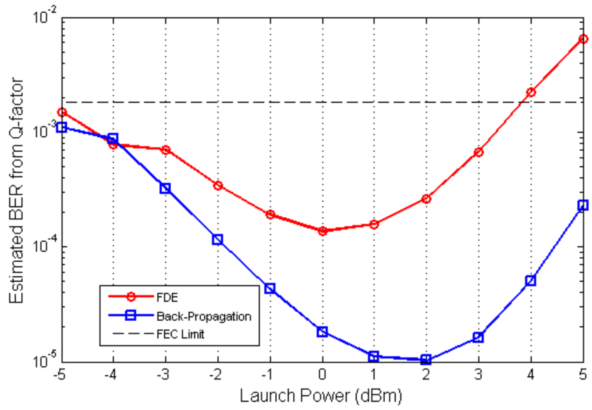


Fig. 5. Comparison of estimated BER between linear compensation only (red) and digital back-propagation (blue) at 800 km

Fig. 6. shows OSNR penalty for each launch power compared to back-to-back for linear equalization only and the DBP implementation. The OSNR was measured at the maximum reached distance for each launch power for a BER of $1.8\ 10^{-3}$. The OSNR gain in the launch power of 2 dBm is 2.6 dB. There is a constant OSNR required gap about 3.5 dB between linear equalization and back-propagation for launch power higher than 3 dBm, this is likely due to the growing influence of high order nonlinear effects that have greater impact over transmission at higher launch powers.

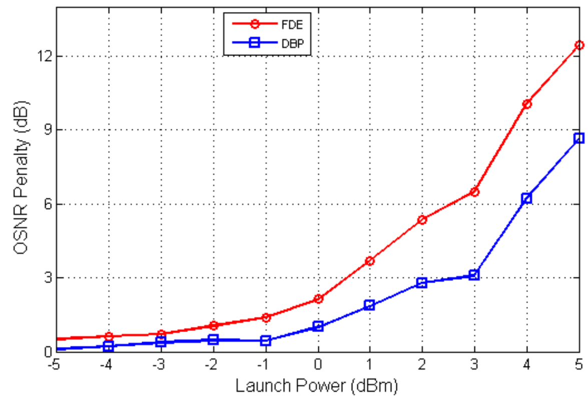


Fig. 6. Comparison of OSNR penalty between linear compensation only (red) and digital back-propagation (blue) at 800 km

Fig. 7. shows the maximum reached distance considering the FEC limit of $1.8\ 10^{-3}$ for each launch power. The peak of the red line, corresponding to linear equalization only, is at 0 dBm as expect from Fig. 5. and corresponds to 1700 km. By using the DBP algorithm to compensate for SPM we reached 2300 km at a launch power of 2 dBm which corresponds to an increase of 35% in maximum reach.

In our analysis of maximum distance reached we have implemented the CBP algorithm to compare with the classical DBP. In order to verify the reduction of computational complexity, we adjusted the parameters of the algorithm to achieve approximately the same BER with the minimum number of steps. This reduction is also shown in Fig. 7. At the launch power of 2 dBm CBP uses only 15 steps instead of 23 steps employed by common DBP. The reduction of computational complexity using CBP was approximately 35%. As expected, it is more difficult to reduce the complexity at higher launch powers because of increasing nonlinear effects impact.

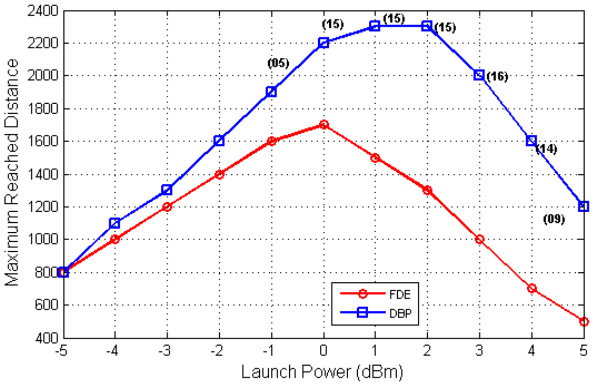


Fig. 7. Comparison of maximum reached distance between linear compensation only (red) and digital back-propagation (blue) at 800 km

In our implementation of the CBP algorithm, we fixed T equal to three. Further increasing in the number of considered symbols did not improve system's performance. For each launch power, b_n is chosen to allow the minimum number of steps. In addition, we employ the same value of b_n for every symbol, giving to the filter described by the weighting coefficients a rectangular shape. Table I shows b values and the complexity reduction of CBP in comparison to one step per span back-propagation. To calculate the computational complexity, we consider only the amount of complex multiplications.

TABLE I. OPTIMAL COEFFICIENTS AND COMPLEXITY REDUCTION OF CORRELATED BACK-PROPAGATION ALGORITHM.

Launch Power (dBm)	DBP steps	CBP steps	Complexity Reduction (%)	b_n
-1	19	05	73.7	0.008
0	22	15	31.8	0.010
1	23	15	34.8	0.014
2	23	15	34.8	0.018
3	20	16	20.0	0.018
4	16	14	12.5	0.02
5	12	09	25.0	0.02

VII. CONCLUSION

On this paper we described the digital back-propagation (DBP) algorithm for nonlinear effects compensation and compared it with the typical linear compensation using frequency domain equalizer (FDE) in the context of a PDM-16QAM 224 Gb/s optical transmission. Transmission performance was significantly improved with DBP, decreasing OSNR penalty by 2.6 dB and increasing maximum reached distance in 35%.

An analysis of CBP algorithm was made to verify the reduction of computational complexity. Despite the significant reduction observed, the computational complexity remains the major impediment to practical applications. The need for knowledge of optical fiber parameters is also a problem to be overcome, perhaps with nonlinear adaptive algorithms.

ACKNOWLEDGMENTS

To FUNTTEL and CPqD for funding and support.

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