Nonlinear Effects Mitigation for a PDM-16QAM 224 Gb/s Transmission systems using DBP and MLSE

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Abstract — **High order modulation nonlinear effects has been appointed as the main limitation in coherent optical fiber transmission. Many different approaches has been investigated to cope with nonlinear effects in optical systems and the most studied method for coherent systems is the digital back-propagation algorithm. MLSE methods have also been effective in combating nonlinear impairments; however it has only been implemented for 112 Gb/s QPSK systems. In this paper, we perform, for the first time, a maximum likelihood sequence estimator (MLSE) in the context of an experimental PDM-16QAM transmission and compare the result with Digital Back-propagation equalization. Also, the use of a combination of both methods is proposed, which increases the distance reached in over 40%.**

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

I. INTRODUCTION

Long-haul optical systems have been pushed to the limit of its current capacity due to the growing data traffic from broadband internet applications and the increasing number of connected devices. Aiming to meet the growing demand, high-order modulation formats with polarization multiplexing (PM) and coherent detection leads to spectrally efficient system that enables (ultra) long-haul optical transmission. A coherent receiver structure preserves all information of optical field (amplitude, phase and polarization), which can be explored by digital signal processing (DSP) techniques to compensate most transmission impairments [1] leading to great achievements in either distance and channel capacity [2]. After the efforts made to compensate major linear system impairments such as polarization mode dispersion (PMD) and chromatic dispersion (CD), the next limit in ultra-long-haul transmission is the nonlinear effects imposed by the optical fiber. As a result, a number of recent works are devoted to nonlinearity mitigation using DSP [3][4][5].

The most significant nonlinear effects presented in a single channel transmission are Self-phase Modulation (SPM) and Intra-Channel Cross Phase Modulation (IXPM). These effects cause phase rotation in the signal, which is dependent of the instantaneous signal power (if SPM) or adjacent pulse power (if IXPM). These effects combined with chromatic dispersion lead to a complex interaction that cause both phase and amplitude distortions in the signal.

Since the nonlinear effects contribution depends on the sum of instantaneous signal power on both polarizations, $|E_{(x,y)}|^2 + |E_{(y,x)}|^2$, an usual method to avoid nonlinearities consists in keeping 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 follows a tradeoff between nonlinear effects and OSNR limitation, which leads to an optimal value refereed as Nonlinear Threshold (NLT). NLT varies widely with fiber parameters and modulation formats.

Many different approaches has been proposed to cope with nonlinear effects in optical systems, including constellation design, nonlinear adaptive equalizers, transmitter pre-distortion, maximum likelihood sequence estimation, and optical or electronic phase conjugation. The most studied method for coherent systems is the digital back-propagation algorithm, which considers the nonlinear term of NLSE to design a digital static equalizer at the receiver, in order to compensate SPM and CD simultaneously [6] [7]. In a previous work [8], a great improvement in terms of both OSNR penalty and distance reached was attained using DBP. On the other hand, MLSE have also been shown to be effective in combating nonlinear impairments; however it has only been investigated for 112 Gb/s QPSK [9]. Higher modulation formats, such as Polarization Division Multiplexing 16-level Quadrature Amplitude Modulation (PDM-16QAM), present an even more challenging situation because the decision thresholds are much closer.

In this paper, the benefit of using MLSE for a PDM 16-QAM experimental system is investigated and compared to DBP. Since MSLE and DBP are not mutually exclusive, they can be combined and the results with the joint employ of both methods are also discussed. We show by experimental results that MLSE offers a gain of 2.2 dB over DBP for a 720-km PDM-16-QAM transmission. When combining MLSE and DBP in the same setups configurations, a gain of 2.85 dB over DBP is attained. In addition, for a fixed Input Power of +3 dBm, we observe that DBP doubles the distance reached by the case in which only linear equalization is performed; but by using MLSE and DBP together, such distance almost triples.

II. MLSE AND DBP IMPLEMENTATION

In this session, we present the two methods of compensation of nonlinear effects used in this work. We introduced conceptually how the methods perform nonlinear compensation and present how we implemented them in our PDM 16QAM scenario.

A. *MLSE Implementation*

The nonlinear effects along with residual CD and PMD can be understood as a specific form of inter symbol interference (ISI) that distorts the optical signal so that the symbols suffer interference from its neighbors. This inter symbol interference can be described trough probability density functions (pdfs). The idea of Maximum Likelihood Sequence Estimation is to utilize these pdfs to describe the signal as a conditional sequence, and not as separate symbols. Training is required to compute the channel statistics and to estimate the channels conditional pdfs. Afterwards we use a maximum likelihood criterion to estimate the sequence of received symbols. The MLSE estimation process employs the Viterbi algorithm which is implemented by establishing M^n possible states, where M is the number of signal constellation points and n refers to the memory length. Each transition between states is related with one of the pdfs of the channel. An example of Viterbi algorithm decision process is shown in Fig. 1.

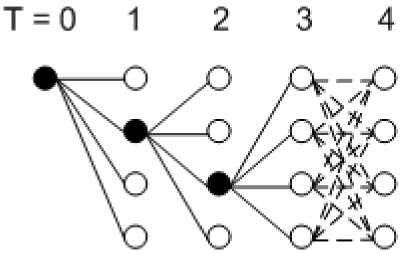

Fig. 1. Example of a Viterbi algorithm decision process for a simple four possible states case

There are several ways to estimate the signal's pdf in order to perform the Viterbi Algorithm at MLSE. In general it is quite common to consider the received pdf to be approximately Gaussian [10]. Thus, the determination of the signal's pdf becomes simply the mean and variance estimation of this Gaussian. In this work, instead of Gaussian approximation, a training sequence is used to build the histogram of the received signal, with this approach we expect to have a more precise estimation of the pdfs. The received samples are quantized with a resolution of 4 bits for real part and 4 bits for imaginary part, producing a 2-D histogram with 16x16 possible bins for each possible state transition. The number of occurrences in each bin is counted and an estimate of each pdf is provided by considering each transition. This procedure requires a state model with M = 256 for the complete characterization of the PDM-16QAM signal, which requires an enormous computational effort. However it is possible to reduce the complexity, by considering the two polarization signals separately (M = 16). In this work we consider a 3-symbol memory system (n = 3), which gives 4096 states for each polarization. A direct consequence of this approach is that it is not possible to fully compensate Intra-Channel Cross Phase Modulation (IXPM), but, on the other hand, it is expected a good balance between performance and implementation complexity. **Erro! Fonte de referência não encontrada.** shows all sixteen histograms derived for the transitions of the first state of the system, that is, '00000000'. Since we have 4096 states for each polarization, we have to construct this same amount of histograms.

The main problem with MLSE is the need of a large amount of memory to save the histograms and the estimated sequence. In this work, for example, we have 4096 states and, consequently, 4096 histograms, each one with 256 bins that counts the number of occurrences. If this number is represented with 8 bits, we need $4096 \times 256 \times 8 = 1\,MB$ (1 megabyte), without considering the estimated sequence length.

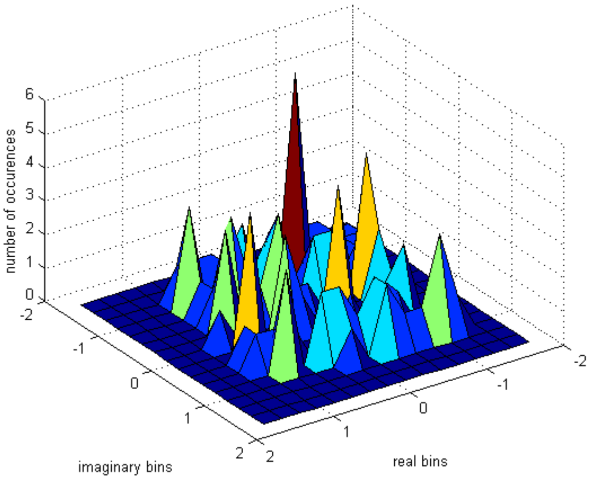

Fig. 2. Histogram of all possible transitions from the first state of the system, '00000000 '

B. *DBP Implementation*

The digital back-propagation algorithm (DBP) is implemented by using a non-interactive asymmetric Split-Step Fourier Method (SSFM), splitting the nonlinear Schrödinger equation into linear and nonlinear inverse components [6]. Instead of solving the entire NLSE, the linear and the nonlinear term, given by (1) and (2), respectively, are solved separately. The chromatic dispersion compensation is provided by a linear filter in the frequency domain, derived from (1). This procedure can only be applied if the impact of the linear distortion does not affect the nonlinear operation and vice-versa. Consequently, a step-size corresponding to the fiber length between amplifiers must be adopted for each equation. In this work it corresponds to 72.316 km.

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

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

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 transforms (FFT and IFFT). Fig. 3. shows a schematic of the BP equalizer.

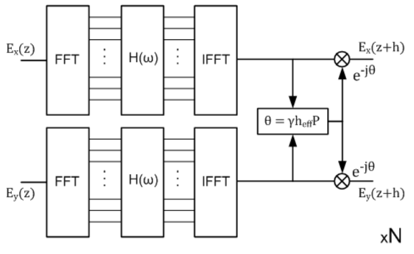

Fig. 3. - Step of back-propagation algorithm with linear equalization in frequency domain and nonlinear equalization in time domain.

The computational complexity for DBP scales linearly with the number of spans between the EDFAs presented in the optical systems. Various methods were presented to try to overcome these problems, but no definite solution was found yet [11].

Since both methods operate on different principles, DBP tries to invert the effects introduced by the channel and MLSE tries to remove ISI of any nature, they both could work together to achieve even better results. Future studies shall attempt to reduce the complexity when combining both methods. For example, by employing a DBP with $steps < span$, i. e., with fewer steps than spans, combined with a MLSE with reduced number of states.

III. EXPERIMENTAL SETUP

Fig. 5. depicts the experimental system scheme including transmitter (A), optical link and receiver structure (B) for a PDM-16QAM system at 224 Gb/s. Fig. 5. (C) presents the received constellations for a back-to-back transmission. 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 combiner (PBC) and sent over the transmission link. The transmitted sequences are a pseudo random pattern with length 2^{15} - 1.

The link consists of an optical recirculation loop of 72.316 km of pure silica fiber and an erbium doped fiber amplifier (EDFA) with a noise figure of 5 dB which is adjusted to fully compensate the attenuation of the link. The fiber has attenuation (α) of 0.2 dB/km, dispersion (D) of 18.4 ps/nm/km, and a nonlinearity coefficient (γ) of 1.5 W/km. For the sake of simplicity, third-order dispersion effects (slope) were not considered.

After fiber transmission, the received signal was pre-amplified (constant power of 0 dBm), then filtered by using a 200 GHz bandwidth 4th order Gaussian optical band-pass filter, and finally passed through a PBS. Each polarization component was then coherently detected by an electrical-optical hybrid (EO Hybrid) and two pairs of balanced photodiodes. The local oscillator laser has a linewidth of 500 kHz. The received electrical signals are sampled and digitalized using a real time scope with sampling rate of 40 GS/s and electrical bandwidth of 20-GHz. Eight data sets of 80-kS are acquired and processed offline for each round trip at recirculation loop.

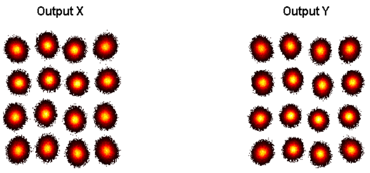

Fig. 4. BER comparison between the three methods: varying Distance at a Input Power of 3 dBm

An all optical method is used for generate the PDM-16QAM signal, which uses a QPSK signal passing through a linear polarization filter in a certain angle so that a square 16QAM can be achieved. Afterwards, a polarization multiplexer is used in order to produce a dual polarization signal. This is a stable and straightforward all optical way of generating a PDM-16QAM without the need of a Digital-to-Analog Converter (DAC) [12]. Unfortunately, one drawback of the method is that the constellation points do not stay in their exactly correct position, as shown in figure Fig. 4. 4, where "Output X" and "Output Y" are the constellations for each polarization; which leads to some loss on the system.

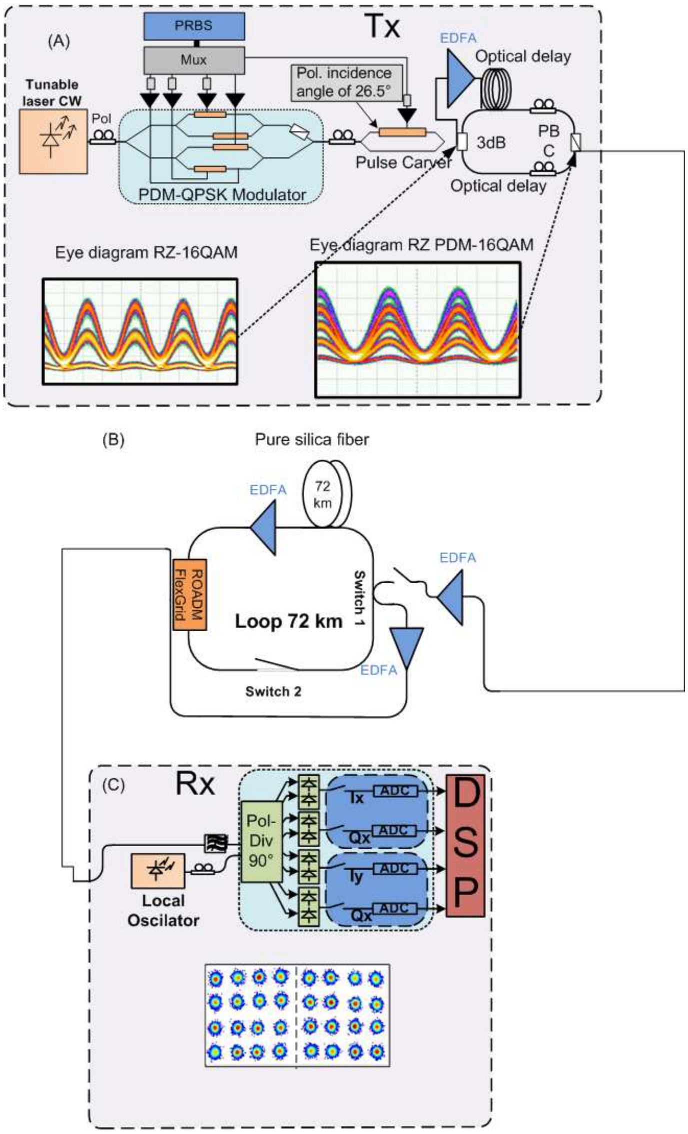

Fig. 5. Experimental system schematic: (A) transmitter setup, (B) coherent receiver, (C) Back-to-Back received constellations for each polarization

A set of digital processing techniques need to be employed to recover the transmitted data from these sampled received signals, which is performed offline with MATLAB . The first step is an orthonormalization procedure that compensates front-end imperfections such as inaccuracies in the optical hybrid that can lead to crosstalk between in-phase and quadrature components on each received polarization. Following orthonormalization, static equalization is applied, in order to compensate the deterministic effect of CD, using a conventional Chromatic Dispersion Frequency Domain Equalizer (CD-FDE) [14]. As stated by the previous session, when DBP is tested, it substitutes CD-FDE therefore performing both chromatic dispersion and nonlinear effects compensation. 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, and signal interpolation. A dynamic equalization is necessary 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. In our case, the dynamic equalizer (DE) is updated by a conventional Constant Modulus Algorithm (CMA) for pre-convergence and then refined using a Radius Directed Equalizer (RDE) [13]. Finally, carrier recovery is performed. The first step to carrier recovery is Frequency Offset Estimation and Compensation, to identify and fix frequency mismatches between transmission and local oscillator 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. When MLSE is not used, symbols are decided based on simple thresholds. The whole process of linear compensation is depicted on figure 6.

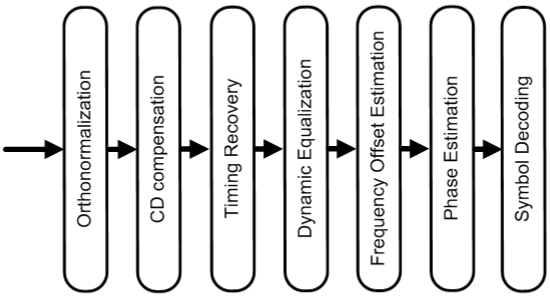

Fig. 6. Digital signal processing for coherent systems (linear equalization)

The experimental analysis of the compensation performed by the back-propagation algorithm and the MLSE method are made by varying the launch power at transmission from -3 dBm to +3 dB. The presented results are an average of the performance of the eight data sets for each lap in the recirculating loop.

IV. RESULTS AND DISCUSSIONS

First, we test the hypothesis that the drawback due to the method employed in generating the PDM-16QAM signal may be overcome by using MLSE, since the estimator can compensate any form of intersymbol interference. We performed a back-to-back experimental test, linking the transmitter and receiver of Fig. 5. directly, without using any fiber and therefore without any presence of nonlinear effects. Using linear equalization only, we have achieved a mean BER of $2.6\ 10^{-4}$ with 20 different sets of data. When we use MLSE, with the same sets of data, we have achieved a mean BER of $1.57\ 10^{-4}$, which confirms MLSE as a good method to improve DP-16QAM systems implemented as [12].

Fig. 7. shows BER using linear compensation only, MLSE and one step-per-span digital back-propagation for a 720 km experimental link. In this experiment, linear compensation alone was not able to bring the BER below the FEC Limit established at $4.0\ 10^{-3}$. In the case of the DBP implementation, we assume that α, β_2, β_3 and γ are known at the receiver. As we should expect, the gain using DBP increases with higher launch powers, due to the impact of nonlinear effects. Launch powers above -1 dBm present an increasing penalty, which indicates that the implemented algorithm does not fully compensates nonlinear effects, such as IXPM of high orders, IFWM or even the interactions of these effects with noise.

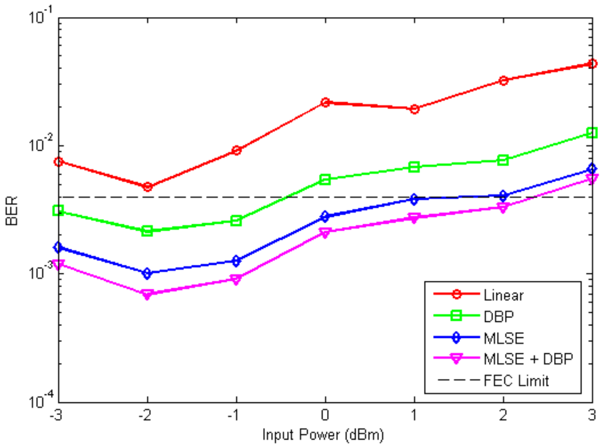

Fig. 7. BER comparison between the three methods: varying Input Power at 10 laps on the recirculating loop (approximately 720 km)

DBP presented results below the FEC Limit for Input Powers up to -0.5dBm. MLSE presented better results than DBP for all Input Powers, offering a gain of 2.2 dB. This performance can be explained by the inaccuracy of the DBP model, that is, due to imprecise values of α, β_2, β_3 and γ, or to a poor decision of the step length as well as the improvement in placing the correct constellation points. The application of the MLSE method along with the DBP algorithm achieved an even better result, as expected, presenting a gain of 0.65 dB, if compared to the MLSE implementation.

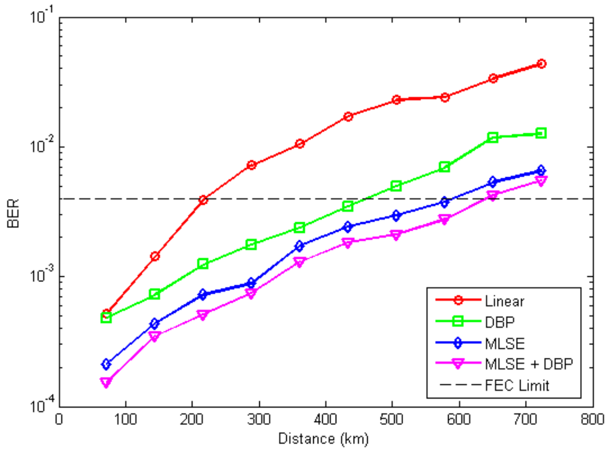

Fig. 8. BER comparison between the three methods: varying Distance at a Input Power of 3 dBm

Fig. 8 shows the comparison between the methods for a Input Power of 3 dBm. Using linear equalization only, the system had BER below FEC Limit up to 215 km. The gain using DBP was significant, improving the reached distance up to 460 km. This corresponds to more than twice the previous reached distance. The result using MLSE was even better, since the distance reaches 590 km. When both methods are used together, the distance reaches 640 km, almost three times we obtained with linear equalization only.

V. CONCLUSION

In this paper, we presented and discussed the implementation of the MLSE method for mitigating nonlinear impairments in a PDM-16QAM transmission scenario. To the best of our knowledge, it is the first time that MLSE is practically tested in such scenario. The results were compared with the typical linear compensation and with nonlinear compensation based on the digital back-propagation algorithm.

We also show that MLSE has been able to improve the drawback of all-optical generated PDM-16QAM that do not use digital-to-analog converters. We demonstrated a gain up to 2.2 dB in Input Power compared to the DBP implementation and, when both methods were implemented together, we have shown an improvement of 2.85 dB, if compared to the implementation of only DBP. In terms of maximum distance reached, DBP doubled the distance compared to linear equalization only, while a combination of both methods almost triples it, for a transmission with +3 dBm of input power.

Suggestions for future studies include methods to reduce the computational complexity when combing DBP and MLSE in real time applications.

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