Blind Source Separation in Polarization Division Multiplexed Optical Systems

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Abstract— **Polarization division multiplexing systems is a promising technique, able to double the capacity of next generation optical communication systems. However, the most common employed algorithms to recover the sources from the received data have the drawback of losing sources when polarization dependent loss is present. To tackle this problem, we propose different approaches based on independent component analysis algorithms.**

Keywords- Polarization division multiplexed optical systems; blind source separation; independent component analysis.

I. INTRODUCTION

Most deployed high capacity optical communication systems are working with up to a hundred wavelengths spaced by 50 GHz, working at 10 Gb/s per channel. These systems usually present a binary amplitude pulse modulation, direct detection receiver, and few, or more likely none, digital signal processing to equalize channel impairments [1]. However, such modulation format has a poor spectral efficiency, and further upgrade in channel bit rate will be restricted in dense wavelength division multiplexed (DWDM) systems. To cope with constant demand for higher data rates, the next generation optical systems, working at 40Gb/s per channel, will need more spectrally efficient modulation formats, e.g. PSK and QAM. However, the direct detection receivers cannot recover the phase encoded information. One possibility is to employ differential interferometer receivers, but they are able to recover only differential PSK formats.

Coherent receivers are an attractive choice to detect amplitude and phase encoded information in any format. Besides, it also recovers the full information of the incoming optical signal, which allows a fully equalization of channel impairments by Digital Signal Processing (DSP), what is not possible with direct or differential detection. The digital equalization of channel impairments will be a major concerning in the next generation optical systems to overcome residual Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD), among other linear impairments. Coherent detection also allows exploring the fiber polarization diversity, what has been seen as another promising strategy to increase the spectral efficiency of lightwave systems. The electrical field of the optical signal can be modulated along two orthogonal axes. Encoding different data along each polarization, i.e. using Polarization Division Multiplexing (PDM), doubles the number of bits transmitted per wavelength. A 40GB/s PDM DQPSK transmitter scheme is shown in Fig. 1.

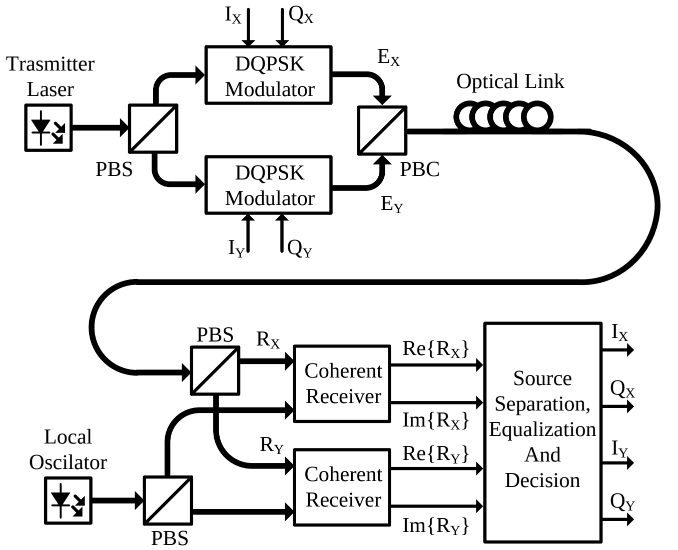

Figure 1. Scheme of a Polarization Division Multiplexed DQPSK modulated Optical System.

The light generated by the laser is firstly split in two rays, being each light signal sent into two independent DQPSK modulators. Each modulator is driven by two binary electrical signals at 10GB/s, one for in-phase and another for quadrature information. Then, the optical modulated signals are combined through a Polarization Beam Combiner (PBC) along two orthogonal polarizations. At the receiver end, the orthogonal polarizations are separated through a Polarization Beam Splitter (PBS) and each signal is detected by an optical coherent receiver, which recovers the four 10GB/s data streams. This scheme has the advantage of increasing the overall bit rate while keeping all the electrical signals at 10Gb/s, which allows analog-to-digital conversion with current technology and paves the way for digital signal processing techniques. Moreover, it also limits the symbol rate at 10Gbouds/s, improving the system robustness to channel impairments [2].

Along the fiber, the State of Polarization (SOP) of a lightwave is usually not preserved, leading to random coupling between the two data streams. Hence, the outputs of the PBS

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are, indeed, a mixture of the transmitted data. To avoid interference between polarizations and perform equalization of linear impairments, a number of works have been considering the application of signal processing techniques to PDM systems. In most of these works, source separation and equalization are performed at the same time in a MIMO FIR structure, which can be adjusted, for instance, by a multi-user version of the Constant Modulus Algorithm (CMA), Radius Directed Equalization (RDE), or other blind approaches [3,4]. After convergence, a Decision Directed (DD) algorithm is often employed to refine the obtained solution [5,6]. A main limitation of these algorithms comes from the presence of high Polarization Dependent Loss (PDL) on the optical link, which may lead to a strong correlation between the received data. In such a scenario, the above-mentioned algorithms may not be able to recover all sources. Moreover, their convergence speed is also compromised.

Recently, methods based on Independent Component Analysis (ICA) were applied to perform Blind Source Separation (BSS) in presence of PDL, with post equalization of linear distortions. ICA-based solutions have stronger separation criterion than usually employed algorithms, and has been shown that ICA can retrieve the sources even on high PDL, and could also track fast changes in the signals state of polarization. However, previous works employing ICA on these systems considered an instantaneous mixture model [7], which is valid only in low dispersion scenarios. In a more general case, the received signals are actually convolutive mixtures of the sources, which limit the effectiveness of the previous approach.

In this work we propose the use of ICA-based solutions to solve the polarization mixture problem in PDM optical communication systems, even in high dispersion scenarios. We employ two different ICA algorithms, one for instantaneous and another for convolutive mixture models, and compare their performance with the multi-user CMA. The source loss probability in presence of PDL, and the effectiveness of the equalization of CD and PMD, will be evaluated for each algorithm.

II. Optical Channel Model

Chromatic Dispersion is the main source of intersymbolic interference when operating at the linear domain. Different spectral components of an optical pulse travel with different group velocities, causing pulse broadening and intersymbolic interference. CD is a linear operation usually modeled as

$$CD(\omega, l) = \exp\left(-jD\frac{\omega^2\lambda^2}{4\pi c}l\right), \quad (1)$$

where D is the dispersion parameter of the fiber, λ is the carrier wavelength, c is the speed of light, ω is the angular frequency of the signal, and l is the length of the fiber [5]. For a given pulse, the amount of dispersion increases linearly with the length of fiber, and also increases with the pulse spectral width. The dispersion parameter for each polarization can be slightly different, what leads to dispersion group delay between polarizations when accumulated CD is high enough.

CD is usually equalized in optical domain, by Dispersion Compensation Fibers (DCF), Bragg Grating Filters or even interleaving transmission fiber with opposite dispersion parameters signs. This optical domain approach has the advantage of allowing the equalization of many wavelengths multiplexed on the fiber at the same time. Although this technique is very effective to counterbalance high amounts of dispersion, a residual distortion remains due to the impossibility of exactly compensating all wavelengths – each one having a different accumulated dispersion – with a single optical equalizer. This residual dispersion may be striking at high symbol rates like 10Gbaud/s, so that additional optical or digital equalization of the demultiplexed lightwaves becomes imperative.

Polarization Mode Dispersion is another physical phenomenon in the fiber that may degrade high bit-rate transmissions. As the cross section of an optical fiber is not circular, the fiber has a small birefringence, and consequently, the light velocity may slightly change depending on its polarization. This phenomenon may cause time broadening by generating a Differential Group Delay (DGD) between the two parts of the pulse: one aligned along the slow axis and the other one along the fast axis. That results in pulse distortion and intersymbolic interference. DGD is also known as first order PMD, and can be modeled as

$$\begin{bmatrix} R_X \\ R_Y \end{bmatrix} = \begin{bmatrix} \cos\theta & -sen\theta \\ sen\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e^{j\omega\tau} & 0 \\ 0 & e^{-j\omega\tau} \end{bmatrix} \begin{bmatrix} \cos\theta & -sen\theta \\ sen\theta & \cos\theta \end{bmatrix} \begin{bmatrix} E_X \\ E_Y \end{bmatrix}, \quad (2)$$

where E_X and E_Y are the orthogonally polarized electric fields launched on this section of fiber, R_X and R_Y are electric fields on the section fiber output, θ is the angle between the state polarization of the signals and the fiber principal state of polarization, and τ is the DGD parameter [3]. Contrary to CD, which has a stationary behavior, PMD changes with time following the dynamic state of polarization. Regardless of that, PMD induced broadening is relatively small compared with CD effects. A complete model of PDM includes the effect of random coupling between polarizations. This couplings leads to a reduction of the overall pulse broadening, since it exchange the light traveling on the slow and fast polarization axis. As result, a statistical model of PDM leads to a time spread that increases with the square root of the fiber length.

At last, another relevant impairment over PDM systems is the Polarization Dependent Loss, present on passive elements in the optical link, like connectors, couplers and filters. An element with PDL has a stronger attenuation over one polarization axis than another. Such element can be modeled in a similar form as done with PMD:

$$\begin{bmatrix} R_X \\ R_Y \end{bmatrix} = \begin{bmatrix} \cos\theta & -sen\theta \\ sen\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \sqrt{1+\gamma} & 0 \\ 0 & \sqrt{1-\gamma} \end{bmatrix} \begin{bmatrix} \cos\theta & -sen\theta \\ sen\theta & \cos\theta \end{bmatrix} \begin{bmatrix} E_X \\ E_Y \end{bmatrix}, \quad (3)$$

where γ is the PDL parameter. The PDL, in dB is given by:

$$PDL = 10\log\frac{1+\gamma}{1-\gamma}. \quad (4)$$

If an element has a non-zero PDL, the output fields can be correlated depending on the angle between the signal SOP and the device polarization axis. Due to the non-stationary behavior of the state of polarization, PDL effect is time dependent. The impact of PDL is also cumulative, as many components with small attenuations may contribute to a large accumulated PDL.

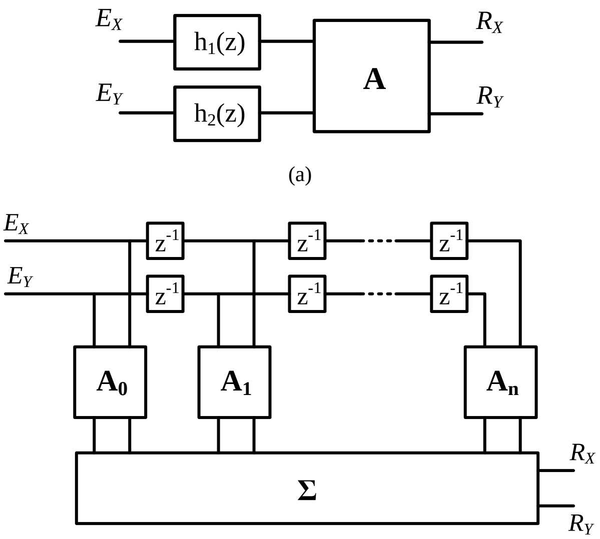
A full channel model including all the described effects is given by:

$$\begin{bmatrix} R_X \\ R_Y \end{bmatrix} = \begin{bmatrix} H_{XX}(\omega) & H_{XY}(\omega) \\ H_{YX}(\omega) & H_{YY}(\omega) \end{bmatrix} \begin{bmatrix} E_X \\ E_Y \end{bmatrix} \exp\left(-jD\frac{\omega^2\lambda^2}{4\pi c}l\right), \quad (5)$$

where H_{ij} is a linear time-dependent filter describing the conjunct effect of PMD and PDL [5], what leads to a linear convolutive mixture model. Even if there is no PMD, the mixture can be convolutive for high values of CD, as the difference of the dispersion parameter on each polarization leads to distinct delays between the received signals.

III. Blind Source Separation in PDM Optical Systems

The main goal in PDM optical systems is to correctly estimate the E_X and E_Y based on the observed signals R_X and R_Y, which is the essence of the BSS problem. If CD and PMD are low enough, we can model the system by an instantaneous mixture matrix, **A**, in addition to SISO filters describing CD and PMD effects. If that condition is not satisfied, we must model the system by a convolutive mixture, composed by a set of mixture matrices, each one associated with a different time delay. Fig. 2 illustrates both models structures.



(b)

Figure 2. Model of instantaneous (a) and convolutive (b) mixture systems.

In PDM optical systems, channel equalization is usually performed by a 2x2 MIMO FIR structure, suitable to deal with both mixture models. In the case of DQPSK modulation, a multi-user CMA is commonly used to adjust the equalizer. The algorithm cost function for the i-th equalizer output is given by:

$$\phi_i = E\left\{\left(\left|y_i[n]\right|^2 - 1\right)^2\right\} + \gamma\left|r_{12}\right|^2, \quad (6)$$

where y_i is the i-th equalizer output, γ is a decorrelation term weight, and r_{12} is the cross-correlation between the two equalizer outputs [8]. The algorithm penalizes this cross-correlation, trying to avoid convergence to the same solution. The addition of this decorrelation term, however, usually makes the convergence slower and increases the steady-state mean square error. Moreover, in the presence of high PDL, the effectiveness of such algorithms is compromised, due to the strong cross-correlation of the incoming signals, leading to a higher probability of source loss.

Another possibility is to employ algorithms based on ICA. The essential idea of this approach consists in exploring the hypothesis that the sources are mutually independent signals, which is a stronger separation criterion that decorrelation. ICA has been successfully used in many application domains, including in optical communication [7].

Essentially, to perform ICA on the observed vector **x** corresponds to finding a matrix **W** for which the components of the separating system outputs ***y***, given by

$$\mathbf{y} = \mathbf{W}\mathbf{x}, \quad (7)$$

are as mutually independent as possible [9]. It can be shown that, if the observed signals correspond to

$$\mathbf{x} = \mathbf{A}\mathbf{s}, \quad (8)$$

where ***s*** denote a vector of mutually independent components (the sources) and **A** denote an invertible mixing matrix, the solution provided by ICA will recover the sources up to permutation and scaling ambiguities [10]. The results obtained for instantaneous mixing systems can also be extended to convolutive systems [11].

There are many well-studied algorithms based on ICA able to deal with instantaneous mixtures, following different independence criteria to find **W** [9], and some of these algorithms were also extended to the convolutive case [13]. Nevertheless, algorithms for the convolutive scenario present a much higher computational complexity than the instantaneous ICA.

We performed a set of simulations in order to compare the conventional MU-CMA [8], an instantaneous FastICA with symmetrical orthogonalization, a well known ICA-based algorithm [9], and a time-domain convolutive version of FastICA, C-FICA algorithm [13]. The ICA-based methods also employ posterior equalization by a standard CMA [13] over the separated signals.

IV. Simulations and Results

The optical system is simulated using the VPItransmissionMaker^{TM} software. We consider a PDM system with a single wavelength at 10 Gbaud/s, in a DQPSK modulation format in each polarization, with a total of 40 Gbit/s. Two optical coherent receivers are employed, and no laser phase noise is present at the transmitter neither the receiver local oscillator. To avoid non-linearity, the transmitted power is set to –1dBm. The power at the receiver is set to –10dBm with a noiseless optical amplifier. The optical link was composed of a 100km optical fiber with variable CD and PMD, and a PLD emulator. For each condition of scenario, at least 100 simulations are performed with 64000 symbols sent on each one. The FastICA algorithm uses a window length of 50 bits with no overlap. C-FICA algorithm uses a kurtosis optimization criterion, with 20 separating matrices. For both ICA-based methods a posterior equalization by a CMA algorithm with a step-size of 0.001 is performed. The conventional structure is based on Multi-User CMA proposed in [13] with a step-size of 0.01.

Fig. 3 shows the probability of source loss for all equalization schemes as a function of PDL, when the CD is 400 ps/nm and no PMD. FastICA exhibits the better performance, successfully separating the incoming signals with no source loss even in a high PDL scenario, while MU-CMA capability to recover all sources decreases strongly with PDL, reaching 40% of source loss with 12 dB PDL. The C-FICA is not stable as instantaneous FastICA, falling to recover the transmitted signals in 10% of the simulations with 12 dB PDL. This behavior is similar to the one observed in dispersion-free simulations.

Despite the better performance in the terms of source loss, the FastICA presents the worst mean square error of the recovered signals for high CD or PMD induced dispersion. This worst performance can be explained by the fact that, for these scenarios, the convolutive character of the mixing process is more pronounced.

Fig. 4 presents the mean square error for all methods in function of accumulated chromatic dispersion. Although FastICA performs better for low Chromatic Dispersion, for CD higher than 300 ps/nm, the C-FICA performs better than MU-CMA and FastICA. It is worth mentioning that such amount of accumulated CD is fairly higher than typical values of residual dispersion in optical compensated systems, so a simpler ICA-based structure could be employed with better results in many practical systems.

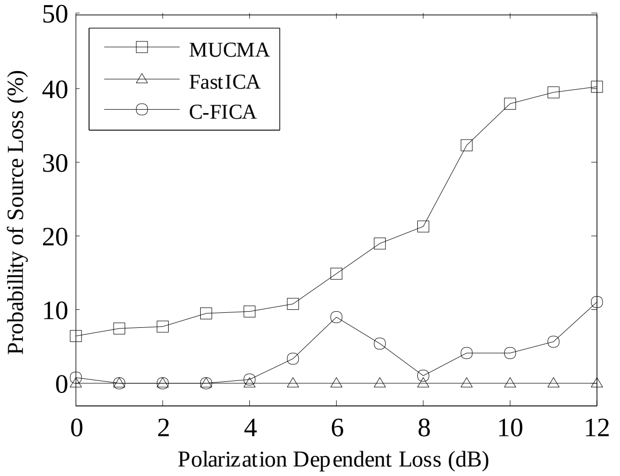


Figure 3. Probability of source loss versus PDL in a 400ps/nm Chromatic Dispersion scenario.

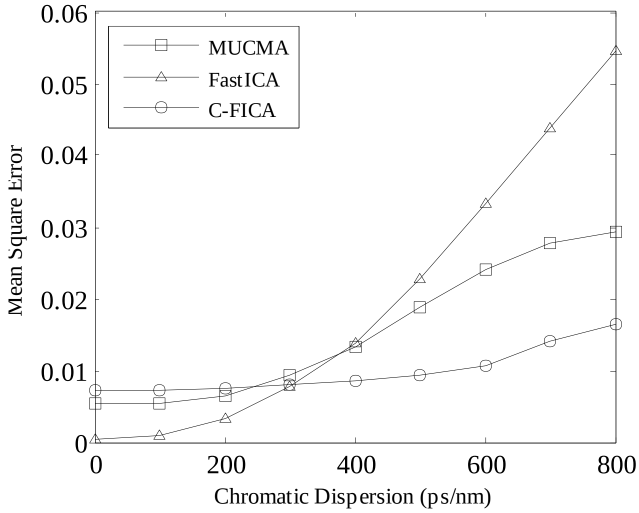


Figure 4. Mean Square Error versus accumulated CD for both methods.

Figure 5 shows a similar result in presence of PMD for a CD free simulation. While FastICA performs better for PMD bellow 30 picoseconds, it is overcome by C-FICA for further dispersions. Again, FastICA is still applicable in some systems with limited PMD, but this constraint is stronger than the one imposed by CD. It's interesting to note that the C-FICA performance gets better as PMD increases in the 0-30 picoseconds interval. This is possibly caused by the small correlation induced by PMD, which makes the signal more suitable for C-FICA algorithm.

The simulations show that the ICA-based solutions are much more resistant to PDL than MU-CMA, exhibiting less, or even none, source loss during signal recovery. The equalization performance of the ICA algorithms is also better than MU-CMA, with instantaneous FastICA shown better results at low CD and PMD, and C-FICA at higher dispersions.

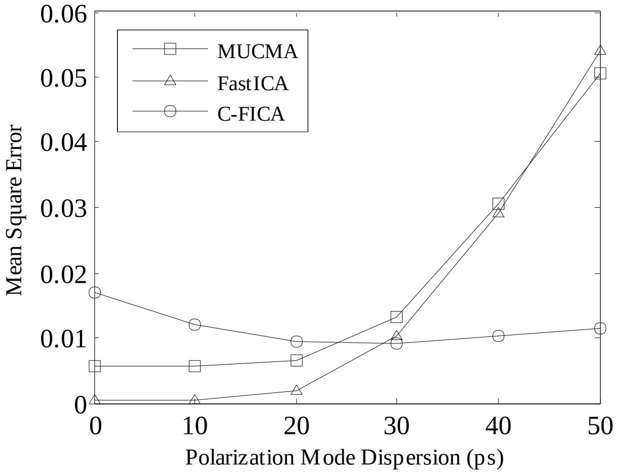


Figure 5. Mean Square Error versus accumulated PMD for both methods.

It is worth to note that these results were obtained if no phase noise from lasers, neither ASE noise from optical amplifier. Since both polarizations have the same phase-noise, it will probably have a minor effect over ICA performance. The ASE noise impact, in other hand, needs to be further investigated, and could limit the ICA effectiveness.

V. CONCLUSIONS

In this work we successfully employed a convolutive ICA algorithm to perform blind source separation in PDM optical systems, recovering the transmitted data even at high dispersion scenarios. We also evaluated the performance of convolutive and instantaneous ICA in presence of CD and PMD, and show the robustness of these algorithms to PDL induced source loss. Optimized convolutive ICA algorithms may lead to better results, in special, keeping the zero source loss probability shown by FastICA, and also to a reduced computational complexity.

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