Polarization Demultiplexing by Independent Component Analysis

Xiaobo Xie, *Member, IEEE*, Fatih Yaman, Xiang Zhou, and Guifang Li, *Senior Member, IEEE*

***Abstract*—Independent component analysis has been applied to polarization demultiplexing for coherent optical fiber communications. Polarization-multiplexed quadrature phase-shift keying and quadrature amplitude modulated signals were successfully demultiplexed by a tensor-based algorithm without using any knowledge of the modulation format.**

***Index Terms*—Coherent receiver, digital signal processing (DSP), fiber-optic communication, polarization demultiplexing.**

I. Introduction

COHERENT optical fiber communication has reattracted researchers' interests in recent years thanks to the fast analog-to-digital converter (ADC) and advanced digital signal processing (DSP). Coherently detected optical fields not only facilitate digital phase estimation but also make it possible to implement impairment compensation in the digital domain [1]–[3]. Moreover, coherent receivers detect both amplitude and phase of the optical field, enabling advanced modulation formats such as quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM). This greatly improves the spectral efficiency of the communication channel. Polarization multiplexing is another way to increase spectral efficiency by transmitting signals through both polarizations of the optical field. However, due to random polarization rotation in optical fiber, two polarizations will be mixed at the receiver even when polarization diversity receivers are used. To successfully decode the transmitted data, polarization demultiplexing has to be implemented at the receiver.

Several methods have been demonstrated to demultiplex data from mixed polarizations, among which are the least mean square algorithm with the help of training sequences [4], the decision directed algorithm [5], and the constant modulus algorithm (CMA) [6]. Blind demultiplexing algorithms such as CMA are desired because no training data are necessary. Using constant modulus as a criterion, CMA is more effective for constant modulus modulation formats than it is for nonconstant modulus formats, such as M-ary QAM. There is also the chance that the two outputs of CMA converge to the same polarization, which defeats the purpose of demultiplexing [7]. Recently, several modified CMA algorithms have been proposed for nonconstant modulus formats [8], [9], but all these algorithms are modulation-format-dependent.

Independent component analysis (ICA) is a method for separating independent signals from mixtures [10], [11]. The only requirement it relies on is that the original signals before mixing have to be statistically independent and only one Gaussian distributed signal is allowed. This general assumption makes ICA fit into broad applications such as voice signal separation, image processing, and multiple-input–multiple-output (MIMO) communications. As coherent optical receivers with polarization diversity can record optical fields in both orthogonal polarizations, ICA can be a useful tool for modulation-format-independent polarization demultiplexing. Polarization demultiplexing based on ICA for coherent optical receivers has been explored [12]. However, the true principle of ICA was not utilized therein. The criterion used there was a match of probability density function (pdf) of a demultiplexed signal to an assumed target pdf. The target pdf, which depends on modulation format and signal-to-noise ratio (SNR), has to be carefully chosen for it to work. This approach makes it modulation-format-dependent. Besides, stochastic gradient descent (SGD) optimization was used in the algorithm, which requires an initial matrix and a step size parameter to start with. Here we demonstrate the application of ICA to polarization demultiplexing using statistical independence as a criterion and with a tensor-based algorithm, which does not need any extra parameters. The algorithm was successfully applied to the experimental QPSK system as well as simulated QPSK and 16-QAM systems.

II. Principle

In a scenario where the output signals are linear mixtures of the input signals, the output and input signals can be related by a matrix. If the inverse transformation matrix can be found, then the input signals can be obtained from the output signals. ICA relies on the assumption of statistical independence of the input signals to evaluate the transformation matrix only from the output signals. In the case of polarization demultiplexing, there are two inputs and two outputs. The ICA criterion can be expressed as follows:

$$p_{xy}(E_x, E_y) = p_x(E_x)p_y(E_y) \quad (1)$$

where p_{xy} is the joint pdf of two orthogonal polarizations while p_x and p_y are marginal pdfs of x and y polarization, respectively. In practice, instead of pdfs, high order cumulants are used to determine statistical independence. According to the central limit theorem, the statistics of a mixed signal tends to

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X. B. Xie, F. Yaman, and G. Li are with CREOL, The College of Optics and Photonics, University of Central Florida, Orlando, FL 32816 USA (e-mail: xiaobo@creol.ucf.edu; fyaman@creol.ucf.edu; li@creol.ucf.edu).

X. Zhou is with AT&T Laboratories-Research, Middletown, NJ 07748 USA (e-mail: zhoux@research.att.com).

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be more Gaussian compared with its independent components. Since high order cumulants of a Gaussian signal are all zero, they can be used to evaluate the Gaussianity of a signal and to be used in ICA.

For the purpose of polarization demultiplexing, the matrix linking the output signals to the input signals is a unitary matrix. A unitary matrix in general has four free parameters [13]. Two of them can be corrected during digital phase estimation, leaving only two parameters to be determined in polarization demultiplexing. Hence, the unitary matrix required for polarization demultiplexing can be expressed as

$$\mathbf{U} = \begin{pmatrix} \cos\alpha & \sin\alpha e^{j\theta} \\ -\sin\alpha e^{-j\theta} & \cos\alpha \end{pmatrix} \quad (2)$$

where α and θ are two free parameters to be obtained.

There are several different algorithms to implement ICA. The tensor-based algorithm uses marginal kurtosis, the fourth-order marginal cumulant, as the indicator to find independent components. The contrast function is defined as

$$\Phi = K_{1111} + K_{2222} \quad (3)$$

where K_{1111} and K_{2222} are marginal kurtoses of the two polarizations. Kurtosis itself is a tensor under unitary rotation. Its dependence on unitary rotation (α and θ) can be calculated analytically [11]. In optical communication, signal pdfs are sub-Gaussian and their marginal kurtoses are negative. The further the marginal kurtoses are from zero, the less Gaussian and more independent the signals are. Therefore, the correct unitary transformation matrix can be found by minimizing the contrast function [14]. The advantage of the tensor-based algorithm compared with SGD is it does not need any initial values and step size to start with and it does not have convergence problems.

III. Simulation and Experiment

The tensor-based ICA algorithm was tested on both simulation and experimental data and showed good performance for polarization demultiplexing.

In our *VPItransmissionMaker* simulation, a laser with 1-MHz linewidth was split into two orthogonal polarizations and each polarization was modulated by 10-GSym/s QPSK or 16-QAM data with an in-phase/quadrature (I-Q) modulator, after which they were combined together. The signal was transmitted through a 100-km-long fiber followed by an erbium-doped fiber amplifier to compensate for the fiber loss. The optical signal-to-noise ratios (OSNRs) were 28 and 25.5 dB for QPSK and 16-QAM, respectively. The dispersion was set to be 16 ps/(km · nm). However, the nonlinerity coefficient was set to zero because it was not the focus of the simulation. The polarization-mode dispersion (PMD) was introduced to only cause a polarization rotation with an insignificant differential group delay (DGD) of 5 ps. At the receiver, a local oscillator (LO) laser with the same linewidth as the transmitter laser was used and combined with data through optical 90° hybrids in two polarizations. Afterwards, four balanced photodetectors were used to record the signal. The sampling rate of the simulation software was 16 sample/symbol.

The recorded data were processed in Matlab and digital dispersion compensation was first applied. The tensor-based ICA was applied next to do polarization demultiplexing. Finally, the signal went through digital phase estimation. In both cases of QPSK and 16-QAM, the constellations were recovered after processing 16 384 symbols. Two parameters in the mixing matrix were calculated to be $\alpha = 38.5°$ and $\theta = -43.0°$. Fig. 1(a)–(c) shows the signal constellation plots for QPSK data before polarization demultiplexing, after polarization demultiplexing, and after phase estimation, for two orthogonal polarizations, respectively. The ICA algorithm un-mixes the received signal and transforms the constellation from multiple circles to constant modulus after polarization demultiplexing. The QPSK data was recovered after phase estimation with Q values of 25.58 and 25.51 dB for x and y polarization, respectively. For 16-QAM data, similar results were obtained as shown in Fig. 2(a)–(c). After polarization demultiplexing, three circles can be clearly identified from the constellation plots, which are the characteristics of 16-QAM signal. The Q values obtained after phase estimation were 16.06 and 16.09 dB for two polarizations. The successful polarization demultiplexing of both QPSK and 16-QAM signals demonstrates the modulation-format-independent nature of the ICA algorithm. The ICA algorithm was tested on both cases of 16 and 1 sample/symbol. The results were very similar. In the case of 16 sample/symbol, the sampled waveforms have transitions from symbol to symbol as a result of the I-Q modulators and, therefore, they are more analog-like. The ICA still works successfully. The algorithm was also tested with different polarization rotations. Since the tensor-based algorithm calculates α and θ analytically,

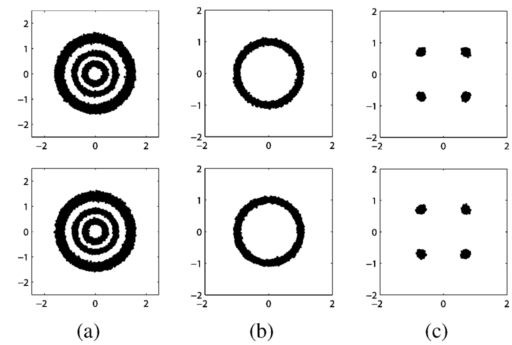

Fig. 1. Signal constellation plots of x (upper) and y (bottom) polarizations for QPSK data (a) before polarization demultiplexing, (b) after polarization demultiplexing, and (c) after phase estimation.

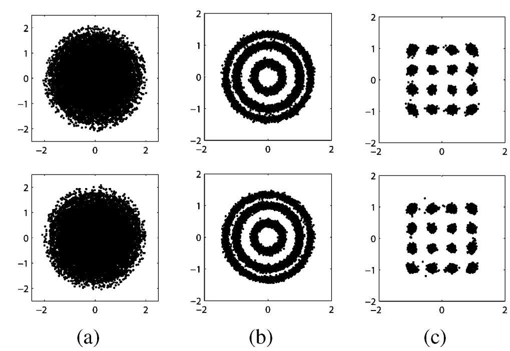

Fig. 2. Signal constellation plots of x (upper) and y (bottom) polarizations for 16-QAM data (a) before polarization demultiplexing, (b) after polarization demultiplexing, and (c) after phase estimation.

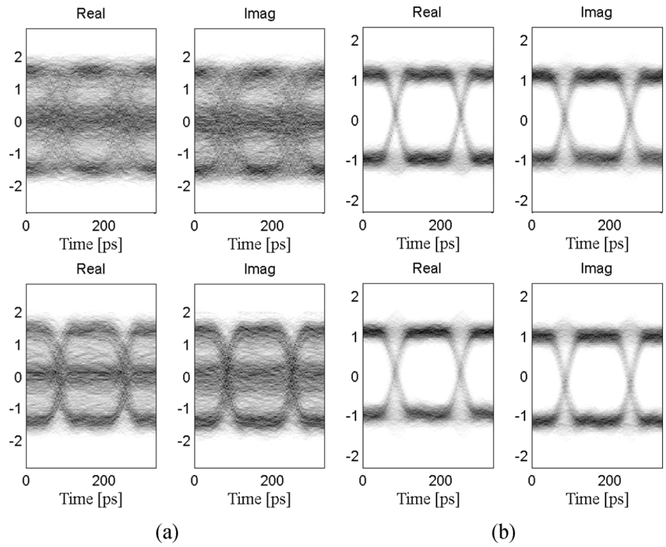

Fig. 3. Eye diagrams of x (upper) and y (bottom) polarizations (a) without and (b) with ICA polarization demultiplexing.

the demultiplexing performance did not show dependence on rotation angles.

To evaluate the minimum number of symbols required in ICA to achieve acceptable performance, we reduced the number of symbols in the processing from 16 384, successively by factors of 2, and for each number of symbols used Q values and symbol error ratios to qualify the performance at high and low SNR conditions, respectively. At high SNR, the Q value decreased gradually in the beginning until it experienced a sharp drop. The turning points were 32 and 256 for QPSK and 16-QAM, respectively. The corresponding Q values were about 0.8 dB less than the case of 16 384 symbols for both formats. At low SNR, the symbol error ratio fluctuated slightly until it increased by an order of magnitude. The number of symbols before jump was 64 for QPSK and 256 for 16-QAM. At both high and low SNRs, the minimum symbol numbers are applicable for real systems where polarization state only changes on the microsecond scale.

The experiment was conducted in a similar way as in the simulation. Only back-to-back transmission was carried out. The signal was modulated by 6-GSym/s QPSK data in two orthogonal polarizations. The linewidth of the transmitter and LO lasers were about 1 MHz. At the receiver, a digital real-time oscilloscope was used as an ADC to record data in both polarizations. The data was resampled at 1 or 2 sample/symbol and then processed by ICA polarization demultiplexing. Again phase estimation was applied afterwards to recover the data. A total of 2368 symbols were used in the processing. Fig. 3(a) and (b) shows the eye diagrams without and with ICA polarization demultiplexing for two polarizations, respectively. The Q values for two polarizations were 17.26 and 17.76 dB after polarization demultiplexing. The values of α and θ obtained were 35.3° and 87.6°. The polarization rotation in the experiment was considered as a constant during short recording time. It is clear that successful polarization demultiplexing was achieved by the tensor-based ICA algorithm.

IV. Conclusion

We used the tensor-based ICA method at the coherent optical receivers to demultiplex signals from two mixed polarizations. Compared with the most popular CMA method, the ICA method is more general and can be applied to different modulation formats. The ICA method can also avoid the CMA problem of converging to the same polarization because two polarizations have to be statistically independent in ICA. The ICA method has the potential to be used to compensate PMD and polarization-dependent loss (PDL) with a 2×2 matrix of filters, and to be combined with nonlinearity compensation when fiber nonlinearity becomes prominent. The disadvantage of ICA is it needs a long data sequence for processing so that the true statistics of the data can be represented.

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