A Robust Deflation based Demultiplexing Algorithm for PSK/QAM Coherent Optical Systems

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Abstract: We propose an adaptation of the CMA algorithm in order to ensure singularity-free transmission independently of the channel characteristics. This adaptation is implemented using a blockwise approach in 112Gbit/s context and valid for PSK/QAM formats.

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1. Introduction

The use of polarization multiplexing (PolMux) in coherent optical systems and multilevel modulation formats such as M-ary quadrature amplitude modulation QAM enables us to increase the spectral efficiency and the transmission bit-rate. The propagation impairments mitigation is ensured by digital signal processing (DSP), that compensates for residual Chromatic Dispersion (CD) and monitors polarization dependent effects such as Polarization Mode Dispersion (PMD) and Polarization Dependent Loss (PDL). Constant Modulus Algorithm (CMA) based Fractionally spaced equalization (FSE) is widely used for Multiple-Input Multiple-Output (MIMO) equalization due to its simplicity and insensivity to the phase of the signal. However, it is well known that this equalizer may converge to the same output at both polarizations[1, 2, 3]. In order to solve this singularity issue, different methods were proposed which rely mainly on i) the algorithm re-initialization after convergence by a well-chosen filter [1, 2] or on ii) a cost function discriminating between the equalized signals [3] or on iii) using the complicated Independent Component Analysis (ICA) [4]. In this paper, we propose a new singularity-free algorithm suitable for QAM and PSK equalization. Based on the principle of deflation introduced in [5] in the blind source separation context, the algorithm extracts the two polarizations one by one. It is well suitable for "block" processing as done in [6] as well as for the standard sample-by-sample processing. It does not require a prior knowledge of the propagation channel characteristics unlike [1, 2].

2. Deflation based CMA equalizer

Let $s_p(n)$ be the transmit data (QAM or PSK) sequence at rate $1/T_s$ on polarization p. Let $y_{p,a}(t)$ be the continuous-time received signal on the polarization p. We have

$$y_{p,a}(t) = \sum_{k=0}^{N-1} s_1(k) h_{p,1,a}(t-kT_s) + \sum_{k=0}^{N-1} s_2(k) h_{p,2,a}(t-kT_s) + b_a(t)$$

where $h_{p,q,a}(t)$ is the channel between the input polarization q and the output polarization p corresponding to the residual CD and PMD, and $b_a(t)$ is the noise. N is the size of the transmit data sequence on each polarization. The time support of $t \mapsto h_{p,q,a}(t)$ is assumed to be $L_f T_s$. By sampling $y_{p,a}(t)$ at twice the baud rate, we obtain the bivariate discrete-time received signal $\mathbf{y}_p(n) = [y_{p,a}(nT_s), y_{p,a}(nT_s + T_s/2)]^{\mathrm{T}}$ where $(.)^{\mathrm{T}}$ stands for the transposition. Then

$$\mathbf{y}_p(n) = \sum_{\ell=0}^{L_f-1} \mathbf{h}_{p,1}(\ell) s_1(n-\ell) + \sum_{\ell=0}^{L_f-1} \mathbf{h}_{p,2}(\ell) s_2(n-\ell) + \mathbf{b}_p(n), \quad \text{for } n = 0, \cdots, N-1$$

where $\mathbf{h}_{p,q}(\ell) = [h_{p,q,a}(nT_s), h_{p,q,a}(nT_s + T_s/2)]^{\mathrm{T}}$ and $\mathbf{b}_p(n) = [b_{p,a}(nT_s), b_{p,a}(nT_s + T_s/2)]^{\mathrm{T}}$.
Let $\mathbf{w}_{p,q}(\ell)$ be the ℓ-th component (of size 1×2) for the fractionally-spaced equalizer between polarizations p and q. As the equalizer is assumed to be of length L, its scalar output associated with the polarization p can be written as:

$$z_p(n) = \sum_{\ell=0}^{L-1} \left(\overline{\mathbf{w}_{p,1}(\ell)} \mathbf{y}_1(n-\ell) + \overline{\mathbf{w}_{p,2}(\ell)} \mathbf{y}_2(n-\ell) \right) = \mathbf{w}_p^{\mathrm{H}} \mathbf{y}^{(L)}(n) \qquad (1)$$

with $\mathbf{w}_p = [\mathbf{w}_{p,1}(0), \cdots, \mathbf{w}_{p,1}(L-1), \mathbf{w}_{p,2}(0), \cdots, \mathbf{w}_{p,2}(L-1)]^{\mathrm{T}}$, and $\mathbf{y}^{(L)}(n) = [\mathbf{y}_1(n)^{\mathrm{T}}, \mathbf{y}_1(n-1)^{\mathrm{T}}, \cdots, \mathbf{y}_1(n-L+1)^{\mathrm{T}}, \mathbf{y}_2(n)^{\mathrm{T}}, \mathbf{y}_2(n-1)^{\mathrm{T}}, \cdots, \mathbf{y}_2(n-L+1)^{\mathrm{T}}]^{\mathrm{T}}$ and where $\overline{(.)}$ and $(.)^{\mathrm{H}}$ stand for complex conjugation and conjugate transposition respectively. The CMA criterion is used to calculate the coefficients $\mathbf{w}_p$ for $p = 1, 2$. We consider a block of duration NT_s, *i.e.*, we have N available vectors $\mathbf{y}^{(L)}(n)$.

The proposed deflation based CMA equalizer can be roughly described as follows: the idea behind deflation is to detect one transmit sequence (let say on polarization 1 via any blind equalizer) and to re-construct the output component associated with this transmit sequence (this reconstruction can now be done since the transmit sequence on polarization 1 is known now and thus a Data-Aided-like channel estimator between polarization 1 and both output polarizations can be carried out). Then the contribution of the input polarization 1 on both output polarizations can be removed. As a consequence, it remains only the contribution of the input polarization 2 that can be detect once again by any blind equalizer. More precisely, we have

1. Set the initial equalizer values $\mathbf{w}_{1,1}^0 = [\cdots, 0, 1, 0, \cdots]$ and $\mathbf{w}_{1,2}^0 = [\cdots, 0, 0, 0, \cdots]$.
2. Run CMA until convergence is reached (the stopping criterion is $\|\mathbf{w}_1^{i+1} - \mathbf{w}_1^i\|/\|\mathbf{w}_1^i\|$ smaller than ε where $\mathbf{w}_1^i$ is the equalizer obtained after the i-th CMA iteration).
3. Calculate $z_1(n)$, compensate for frequency offset and phase (with any existing estimator), and make a decision $\hat{s}_1(n)$ on the transmit sequence $s_1(n)$.
4. Estimate the channel impulse responses $\mathbf{h}_{p,1} = [\mathbf{h}_{p,1}(0)^{\mathrm{T}}, \cdots, \mathbf{h}_{p,1}(L_f)^{\mathrm{T}}]^{\mathrm{T}}$ between input polarization 1 and output polarization p. Thus we have
$$\hat{\mathbf{h}}_{p,1} = \frac{1}{NP_0}\mathbf{T}_s^{\mathrm{H}}\mathbf{y}_p \tag{2}$$
where P_0 is the mean transmit power and $\mathbf{y}_p = [\mathbf{y}_p(0)^{\mathrm{T}}, \mathbf{y}_p(1)^{\mathrm{T}}, \cdots, \mathbf{y}_p(N-1)^{\mathrm{T}}]^{\mathrm{T}}$. Moreover the $2N \times 2L_f$ matrix $\mathbf{T}_s$ is equal to $\mathbf{S} \otimes \mathbf{I}_2$ with the $N \times L_f$ matrix $\mathbf{S}$ whose the n-th row is equal to $[\hat{s}_1(n), \cdots, \hat{s}_1(n-L_f+1)]$, $\mathbf{I}_2$ is the 2×2 identity matrix, and $\otimes$ is the Kronecker product. The estimator given in Eq. (2) will perform well if $\mathbf{S}^{\mathrm{H}}\mathbf{S}$ is close to identity. Such an assumption holds here since $s_1(n)$ is an iid sequence.
5. Calculate the contribution of the input polarization 1 on the output polarization 1 and 2. Thus
$$\hat{\mathbf{y}}_{p,1}(n) = \sum_{\ell=0}^{L_f-1} \hat{\mathbf{h}}_{p,1}(\ell)\hat{s}_1(n-\ell).$$
6. The previously-calculated contribution is subtracted at each polarization: $\tilde{\mathbf{y}}_p(n) = \mathbf{y}_p(n) - \hat{\mathbf{y}}_{p,1}(n)$. Then run CMA until convergence is reached with initialization $\mathbf{w}_{2,2}^0 = [\cdots, 0, 1, 0, \cdots]$ and $\mathbf{w}_{2,1}^0 = [\cdots, 0, 0, 0, \cdots]$.

3. Simulation results

A 112Gbit/s transmission is carried out by multiplexing both polarizations with 16-QAM leading to 14Gbaud transmission per polarization. At the transmitter and receiver sides, a square root raised cosine filters with a roll-off factor equal to 1 i used. A 5-th order Bessel electrical filter with a 3dB bandwidth equal to $0.8/T_s$ was included as the anti-aliasing filter. Neither phase noise nor frequency offset between the signal laser and local oscillator were considered. Finally the signal is sampled at twice the baud rate. The channel is a concatenation of CD, DGD, Polarization State Transformation (PST), and PDL. Therefore the channel frequency response is

$$\mathbf{H}(\omega) = \begin{bmatrix} \sqrt{1+\gamma} & 0 \\ 0 & \sqrt{1-\gamma} \end{bmatrix} \times \begin{bmatrix} \cos(\theta) & \sin(\theta)e^{-i\phi} \\ -\sin(\theta)e^{i\phi} & \cos(\theta) \end{bmatrix} \times \begin{bmatrix} e^{i\omega\tau/2} & 0 \\ 0 & e^{i\omega\tau/2} \end{bmatrix} \times e^{i\alpha\omega^2} \tag{3}$$

In Fig.1, we plot the BER versus θ and ϕ for the standard block (std.)-CMA [6] with optimal step size (on the left) and the deflation based block (def.)-CMA with optimal step-size proposed here (on the right). The block size is $N = 1000$. The equalizer length is 6 (*i.e.* $L = 3$). Two PDL values have been considered (0dB on the top, 3dB on the bottom). One thousand blocks has been tested for each channel realization. The proposed deflation based algorithm enables us to cancel the singularity completely.

In Fig. 2 (resp. 3), we display the BER versus residual CD (resp. number of considered CMA iterations) for the def. CMA and the std. CMA for channel realizations exhibiting no singularity. Both CMA are applied on successive data block, and the CMA at block k is initialized by the equalizer obtained at block $k-1$. We show that the std. CMA and the proposed CMA have the same performance and so no penalty is introduced in absence of singularity. In order to reach the stopping condition $\varepsilon = 5.10^{-3}$, the number of iterations of both algorithms are very close. Nevertheless def.-CMA is a little more complex than std.-CMA due to the step 4. Step 4 has a complexity of $4NL_f = 12$kflops whereas each iteration (for both CMA) needs 76kflops [7]. Moreover the def.-CMA may be applied in the first transmission block to ensure non-singularity and then one can move into the std.-CMA for the rest of blocks.

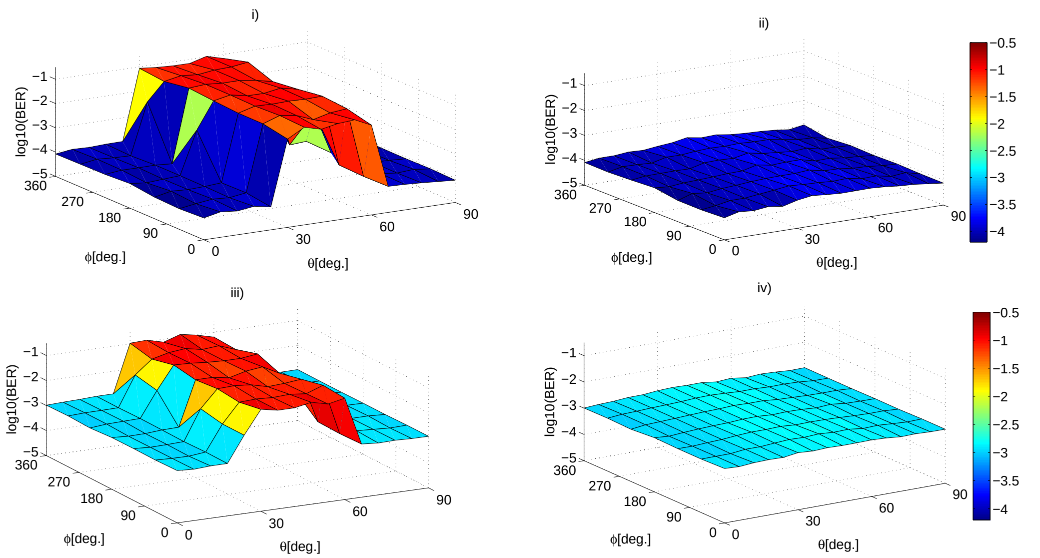

Fig. 1. BER versus θ and ϕ (OSNR=20dB, CD=0ps/nm, DGD=0ps, $N = 1000$): i) PDL=0dB, std.-CMA ii) PDL=0dB, def.-CMA iii) PDL=3dB, std.-CMA, iv) PDL=3dB, def.-CMA.

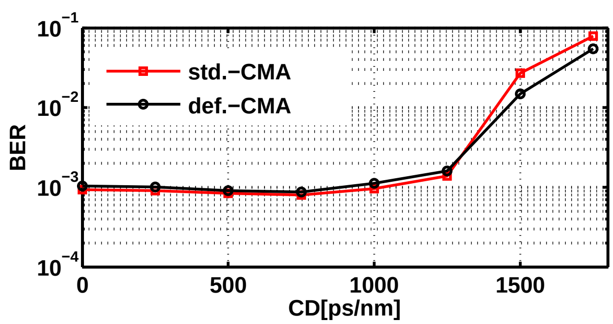

Fig. 2. BER vs. residual CD (OSNR=21dB, DGD=50ps, PDL=3dB, $N = 1000$, $\theta = \phi = \pi/8$)

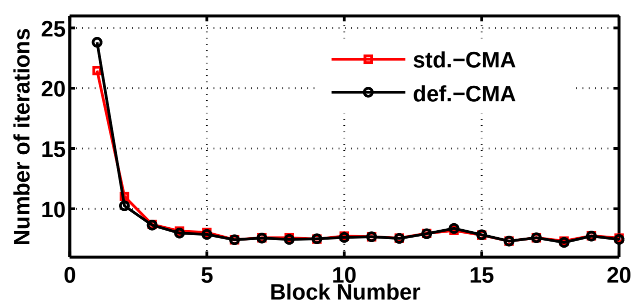

Fig. 3. BER vs. #iterations of equalizers (OSNR=21dB, CD=500ps/nm, DGD=50ps, PDL=3dB, $N = 1000$, $\theta = \phi = \pi/8$)

4. Conclusion

We have proposed a polarization demultiplexing algorithm that operates independently of the optical channel characteristics and that does not introduce OSNR penalty compared to the non singular case.

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