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***Abstract*—We propose a novel method for blind polarization-demultiplexing of probabilistically shaped signals for coherent receivers. The method is capable of separating signals with (quasi) Gaussian distributions by exploiting temporal correlations added to the transmit signals. The proposed method is evaluated in challenging mixing scenarios.**

Keywords—polarization demultiplexing, probabilistic shaping, blind source separation

I. Introduction

Probabilistic shaping (PS) offers considerable gains by adjusting the transmission probabilities of constellation points and enables flexible control over the transmission reach and throughput [1]. However, the advantage of PS comes with a penalty that is paid at the receiver digital signal processing (DSP). Mature DSP algorithms designed for regular or uniform QAM formats do not work well for PS-QAMs [2]. Usually, data-aided (pilot-aided) algorithms for polarization demultiplexing are employed, however, this reduces the net throughput. Therefore, a blind (non-data aided) algorithm is desirable. The problem faced by blind algorithms is that for some ranges of entropies the PS-QAM symbol distribution becomes close to Gaussian, and it is known that a blind separation of Gaussian sources is an intricate problem. This is observed in different ways, e.g., flattened cost function or kurtosis problems in the constant modulus algorithm (CMA) [3], or formation of a sphere- instead of a lens-like structure in Stokes space (SS)-based algorithms, preventing estimation of a correct initialization for a following multi-modulus algorithm (MMA) [4, 5]. Recently, a SS-based algorithm that uses "inner QPSK" symbols to initialize a probability aware multi-modulus algorithm (MMA) was proposed [4, 5]. A similar idea of dividing constellation into two or more parts based on symbol magnitude was proposed in [6]. Very recently, a variational autoencoder-based approach for blind demultiplexing was presented [7].

In this paper, we propose blind polarization demultiplexing of PS-QAM formats using second-order statistics of the signal based on a method given in [8, Ch. 7]. The proposed approach requires a temporal correlation in one of the polarizations at the transmitter and exploits this correlation at the receiver to estimate an initialization for a following MMA. The said correlation was achieved by applying a filter to the transmit signal on one of the polarizations. We evaluate the proposed system in simulations and demonstrate blind demultiplexing of PS-QAM signal in various challenging mixing scenarios where a CMA-based benchmark algorithm fails.

II. Proposed Joint-Diagonalization (JD)

The blind separation of Gaussian sources is impossible unless the sources are mutually independent with a diverse temporal correlation [8, Ch. 7.3]. Let $\boldsymbol{s} = \begin{bmatrix}\overrightarrow{s_1}\\ \overrightarrow{s_2}\end{bmatrix}$ denote a matrix, where $\overrightarrow{s_1}$ and $\overrightarrow{s_2}$ are $1 \times N$ vectors of samples from two uncorrelated wide-sense stationary and second order ergodic processes. The mixed signal is given by $\boldsymbol{x} = \boldsymbol{A}\,\boldsymbol{s}$, where $\boldsymbol{A}$ is a 2×2 linear instantaneous (memoryless) mixing matrix. The autocorrelation of the sources $\boldsymbol{s}$ is given by $\boldsymbol{R_s}(\tau) = \mathbb{E}\{\boldsymbol{s}(t)\boldsymbol{s}^H(t+\tau)\} = \mathrm{Diag}\{R_1(\tau),\ R_2(\tau)\}$, where $R_i(\tau)$ is the correlation sequence of the i^{th} source. It can be shown that $\boldsymbol{R_x}(\tau) = \mathbb{E}\{\boldsymbol{x}(t)\boldsymbol{x}^H(t+\tau)\} = \boldsymbol{A}\boldsymbol{R_s}(\tau)\boldsymbol{A}^H$. If the correlation sequences $R_i(\tau)$ are linearly independent, then the mixing matrix ($\boldsymbol{A}$) and the corresponding separation matrix ($\boldsymbol{B}$) can be estimated by a joint diagonalization of the correlation matrices $\boldsymbol{R_x}(\tau)$ [8, Ch. 7.3.1]. The estimated sources $\hat{\boldsymbol{s}}(\tau) = \boldsymbol{Bx}$ after separation will still have a sign and order ambiguity. Note that this problem is also present in other blind algorithms like independent component analysis (ICA), CMA and SS-PDM. A block-wise method for joint diagonalization [8, Ch. 7.4.1] of the correlation matrices $\boldsymbol{R_x}(\tau)$ is as follows: 1) compute $\boldsymbol{W} = [\mathbf{R}_{\boldsymbol{x}}(0)]^{-1/2}/N$ by using a received symbol block of length N, 2) compute an eigen-vector matrix $\boldsymbol{Q}$ of $\boldsymbol{W}\boldsymbol{R_x}(1)\boldsymbol{W}^{\boldsymbol{T}}$ and 3) compute the inverse mixing matrix $\boldsymbol{B} = \boldsymbol{Q}^{\boldsymbol{H}}\boldsymbol{W}$. The explained joint diagonalization method returns an instantaneous separation matrix $\boldsymbol{B}$ that is used to initialize center taps of the MMA. The MMA returns a 2×2 complex-valued multi-input multi-output (MIMO) filter with memory that is then used to separate the polarizations.

Usually, in communication systems, symbols are independent and identically distributed (iid) and do not have temporal correlation. Therefore, we filter the signal in one of the polarizations at the transmitter. Note that the transmitter components typically have a limited bandwidth response. Hence, this additional filter can also be seen as a cascaded effect of a partial linear digital pre-distortion followed by the limited bandwidth response of the transmitter components. The details of the simulation setup are given in the next section.

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III. Simulation Setup & Results

We compare CMA-initialized MMA (CMA-MMA) with the proposed JD-initialized MMA (JD-MMA) in a proof-of-concept simulation. Sequences of PS 64-QAM 2^{16} symbols generated from Maxwell-Boltzmann distributions at 32-Gbaud (1 sample per symbol) are transmitted over an additive white Gaussian noise (AWGN) channel with polarization impairments. The channel implements either a rotation in the state of polarization (RSOP), i.e. instantaneous mixing, or polarization mode dispersion (PMD) together with RSOP. A differential group delay of 10% of the symbol duration for a 1000 km length of optical fiber was considered for the PMD channel. For simplicity, we omitted the other channel and transceiver impairments in this study. As mentioned earlier, a two-tap filter with coefficients chosen as h = [1, 0.05] is applied to a signal in one of the polarizations at the transmitter. Therefore, JD-MMA always uses MMA with an 11 tap-length to remove this transmit filtering as well as PMD effects if any. The MMA in the CMA-MMA scheme uses tap lengths of 1 for RSOP and 11 for PMD, respectively. One hundred different realizations of both (RSOP and PMD) channels were simulated and performance was assessed using the error vector magnitude (EVM) metric, with transmitted ideal symbols and average constellation power as reference, which is equivalent to inverse signal to noise ratio (SNR). The sign and order ambiguity were resolved by comparing the received and the transmitted symbols. The length of the training sequences for both schemes (CMA-MMA and JD-MMA) was set to 2^{14}. The step parameters of CMA and MMA were chosen as 5×10^{-3} and 5×10^{-4} respectively, which were found to be optimal for uniform 64-QAM symbols.

The average EVMs over the RSOP channel are shown in Fig. 1(a) and (b) respectively. We see that CMA-MMA works quite well for the entropy H=6 bits (i.e., uniform 64-QAM) but does not perform well in the case of PS 64-QAMs (H < 6). We observed that the CMA-MMA failed to converge in many cases. For example, it obtained EVM >-20 dB for 84% of the cases, when the SNR was 25 dB at the entropy H = 4.7 bits. On the other hand, the proposed JD-MMA performs quite well for this range of entropies compared to CMA-MMA. Next, we evaluate both algorithms over PMD channels. In Fig. 1(c), we see that CMA-MMA performance degraded much more in the presence of PMD compared to the RSOP channel (Fig. 1(a)) for H<6, failing to converge in many cases. In contrast, the JD-MMA achieves quite good performance. However, a penalty is observed for the case of the PMD channel compared to the RSOP channel. A careful optimization of the transmit filter might help to improve the JD-MMA performance. The robustness for larger PMD as well as against the impact of other impairments on the proposed JD-MMA requires further investigation.

Summary

We proposed a blind method for polarization demultiplexing of probabilistically shaped QAM signals. The method is capable of separating signals with (quasi) Gaussian distribution, such as PS-QAMs, by exploiting the temporal correlation added to one of the transmit polarizations. The performance of the proposed JD-MMA scheme was compared with CMA-MMA in simulations with polarization mixing and PMD effects. The proposed method can likely be extended for convolutive mixing of signals, thus removing the use of the subsequent MMA. The impact of other impairments on the proposed approach is open for investigation.

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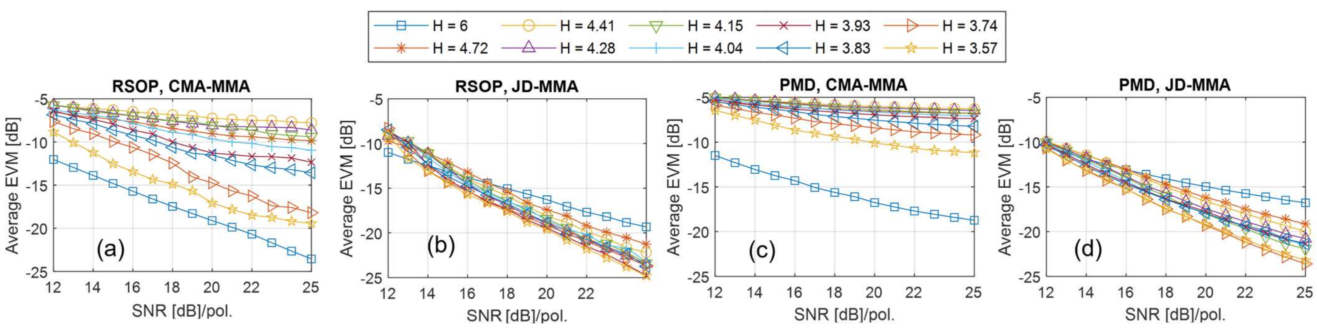

Fig. 1. The performance of CMA-MMA and JD-MMA for different entropies of PS-64QAM, over RSOP channel (a) and (b), and PMD channel (c) and (d).