Differential Phase Compensated Constant Modulus Algorithm for Phase Noise Tolerant Coherent Optical Transmission

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***ABSTRACT* — We extend a non-data-aided constant modulus algorithm (CMA) by a differential phase compensation (DPC-CMA) and simulate its polarization demultiplexing performance in a digital coherent QPSK receiver against that of the standard CMA.**

***Index Terms*— Optical fiber communication, Polarization, Coherent detection, Digital signal processing.**

I. INTRODUCTION

Phase noise is a major distortion in coherent optical transmission systems. The phase noise tolerance of a polarization-multiplexed receiver can be improved by a common carrier recovery (CCR) for both polarizations [1,2]. But this is only possible if the preceding polarization control compensates for the possible phase offset between the two polarizations. While this functionality is inherent in decision-directed polarization controllers, non-data-aided (NDA) algorithms like the CMA do not compensate for this offset [3].

In this paper an extended CMA is proposed that additionally compensates the phase difference between the two polarization channels to allow for a CCR. We compare this differential phase compensated CMA (DPC-CMA) against the standard CMA [4] in a Monte Carlo simulation of a QPSK system.

II. STANDARD CMA AND ITS EXTENSION TO DPC-CMA

The complex input vector $[\underline{Z}_{k,x}\ \ \underline{Z}_{k,y}]^T$ into the polarization demultiplexer is described by

$$\begin{bmatrix}\underline{Z}_{k,x}\\ \underline{Z}_{k,y}\end{bmatrix} \propto \mathbf{J}_k \begin{bmatrix}\underline{c}_{k,x}\\ \underline{c}_{k,y}\end{bmatrix} e^{j\psi_{IF,k}} + \begin{bmatrix}\underline{n}_{k,x}\\ \underline{n}_{k,y}\end{bmatrix} \quad (1)$$

where k is the discrete time index, $[\underline{c}_{k,x}\ \ \underline{c}_{k,y}]^T$ are the transmitted symbols, $\psi_{IF,k}$ is the carrier phase, $[\underline{n}_{k,x}\ \ \underline{n}_{k,y}]^T$ is additive white Gaussian noise (AWGN) and $\mathbf{J}$ is the fiber Jones matrix. In

$$\mathbf{J}_k = \begin{bmatrix} e^{j\delta_k/2}\cos\nu_k & -e^{-j\varepsilon_k/2}\sin\nu_k \\ e^{j\varepsilon_k/2}\sin\nu_k & e^{-j\delta_k/2}\cos\nu_k \end{bmatrix} \quad (2)$$

ν_k describes the polarization crosstalk while δ_k and ε_k denote the phase differences, all of them time-variable.

The signals are sampled at the symbol rate, and perfect clock recovery is assumed. In order to compensate for the polarization crosstalk, the signal must be multiplied at the receiver onto the estimated inverse $\mathbf{M}_k \to \mathbf{J}^{-1}$ of the $\mathbf{J}$,

$$\begin{bmatrix}\underline{Y}_{k,x}\\ \underline{Y}_{k,y}\end{bmatrix} = \mathbf{M}_k \begin{bmatrix}\underline{Z}_{k,x}\\ \underline{Z}_{k,y}\end{bmatrix}. \quad (3)$$

In order to obtain $\mathbf{M}_k$ a NDA approach can be employed, where input and output data of the polarization controller is used to estimate the Jones matrix. In the standard CMA [3] the polarization control matrix $\mathbf{M}_k$ is incrementally updated by

$$\mathbf{M}_{k+1} = \mathbf{M}_k + g\mathbf{T}_k \qquad (0 < g << 1), \quad (4)$$

where $\mathbf{T}_k$ is the polarization control error matrix given by

$$\mathbf{T}_k = \begin{bmatrix} \left(1-\left|\underline{Y}_{k,x}\right|^2\right)\underline{Y}_{k,x} \\ \left(1-\left|\underline{Y}_{k,y}\right|^2\right)\underline{Y}_{k,y} \end{bmatrix} \cdot \begin{bmatrix}\underline{Z}_{k,x}\\ \underline{Z}_{k,y}\end{bmatrix}^+ . \quad (5)$$

Our extended version of the CMA allows the compensation of the phase difference in a coherent polarization diversity receiver. This enables to use one carrier for both polarizations in a CCR. The polarization control matrix $\mathbf{M}_k$ in the DPC-CMA is incrementally updated according to

$$\mathbf{M}_{k+1} = \mathbf{M}_k + g\left(\mathbf{T}_k + \mathbf{U}_k\right), \quad (6)$$

$$\mathbf{U}_k = \begin{bmatrix} -j & 0 \\ 0 & j \end{bmatrix} \mathbf{M}_k \frac{1}{2}\left(\left(\left(\arg\left(\underline{Y}_{k,x}\underline{Y}_{k,y}^*\right) + \frac{\pi}{4}\right) \bmod \frac{\pi}{2}\right) - \frac{\pi}{4}\right). \quad (7)$$

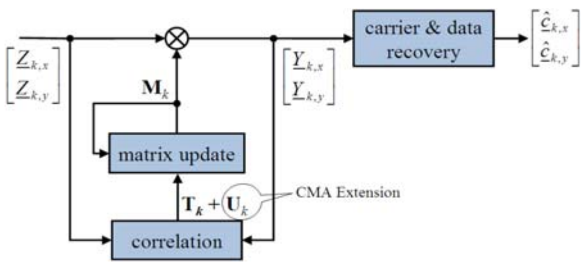

Fig. 1. Non-data-aided (NDA) algorithms for polarization control.

III. PERFORMANCE COMPARISON

The polarization control algorithms are compared in Monte-Carlo simulations of a polarization-multiplexed QPSK transmission system. The 3 Jones matrix parameters in (2) are set by a random number generator and each data point is based on the simulation of $(1\ ...\ 15)\cdot 10^6$ symbols. The sum linewidth divided by the symbol rate equals 10^{-3}.

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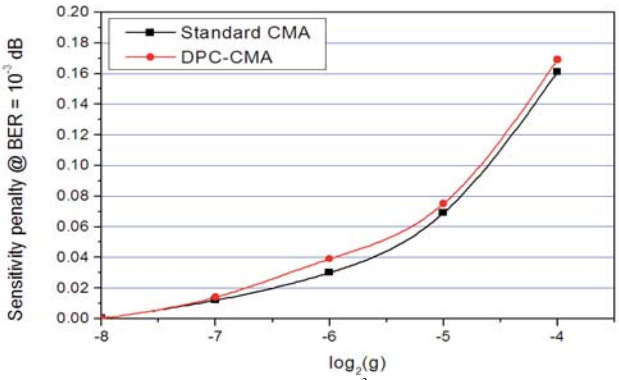

Fig .2 Sensitivity penalty at BER = 10^{-3} for different control gains of the standard and extended polarization control algorithm

Fig. 2 details the influence of the control gain g on the receiver sensitivity for standard CMA and DPC-CMA. The higher the control gain, the faster the polarization controller can track polarization changes. With respect to $g = 2^{-8}$, both CMA and DPC-CMA yield very low penalties up to $g = 2^{-4}$.

Fig. 3 shows BER against OSNR for the standard CMA and the DPC-CMA in combination with three different carrier recovery setups. In combination with separate carrier recoveries (SCR) the filter halfwidths for the two independent phase estimators are set to $N = 3$ and $N = 6$, i.e. 7 and 13 symbols are used for carrier phase estimation, respectively. These setups are compared against one with CCR and $N = 3$, which uses 14 symbols for phase estimation. In the setups with SCR the standard CMA and the DPC-CMA have the same efficiency. However, for $N = 6$ and high OSNR values the sensitivity is affected by phase noise due to the lower filter bandwidth. For $N = 3$ there is a general sensitivity penalty of ~0.2 dB due to a lower phase estimator efficiency. With one

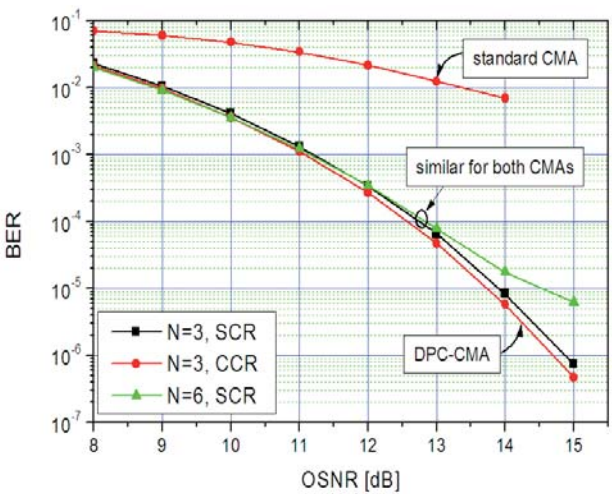

Fig. 3 BER vs. OSNR for standard CMA and DPC-CMA with $g = 2^{-6}$ at different filter widths for common (CCR) and separate (SCR) carrier recoveries

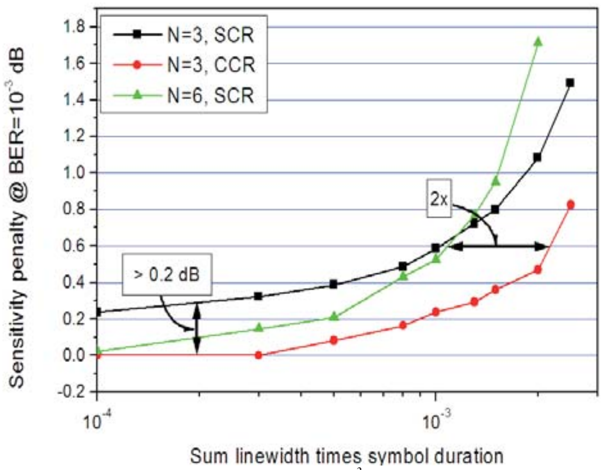

Fig. 4 Sensitivity penalty at BER=10^{-3} for different linewidth times symbol duration products for common/separate carrier recovery

CCR for both polarization channels, DPC-CMA achieves the same sensitivity as for SCR with $N = 6$, but with the same phase noise tolerance as SCR with $N = 3$. However, by design, the standard CMA fails with CCR, given that it does not compensate the phase difference between the two polarizations. Thus the DPC-CMA is required to allow for a CCR.

Fig. 4 also points out the improved performance due to a CCR enabled by the DPC-CMA. It doubles the phase noise tolerance compared to a SCR that uses the same number of symbols for phase estimation or improves the sensitivity by >0.2 dB compared to a SCR with the same filter halfwidth.

IV. Conclusion

In a polarization-multiplexed system the standard CMA can be used only with separate carrier recoveries. But the DPC-CMA compensates the phase difference between the polarization channels. This allows to work with a simpler common carrier recovery in the receiver and thus to improve phase noise tolerance or sensitivity. Both CMAs tolerate high control gains up to $g = 2^{-4}$.

References

[1] R. Noé, "PLL-Free Synchronous QPSK Polarization Multiplex/ Diversity Receiver Concept with Digital I&Q Baseband Processing", IEEE Photon. Technol. Lett., Vol. 17, No. 4, 2005, pp. 887-889.

[2] T. Pfau et al. „Coherent Digital Polarization Diversity Receiver for Real-Time Polarization-Multiplexed QPSK Transmission at 2.8 Gbit/s", IEEE Photon. Technol. Lett., Vol. 19, No. 24, 2007, pp. 1988-1990

[3] D. Godard, "Self-recovering equalization and carrier tracking in two-dimensional data communication systems". IEEE T. Comm.. 1980, Vol. 28, 11, pp. 1867-1875.

[4] K. Kikuchi, "Polarization-demultiplexing algorithm in the digital coherent receiver", Proc. SUM'08. July 21-23, 2008, MC2.2.