Joint Mitigation of Optical Impairments and Phase Estimation in Coherent Optical Systems

L. M. Pessoa, H. M. Salgado and I. Darwazeh

***Abstract*—The electrical compensation of chromatic dispersion (CD) and polarization mode dispersion (PMD) in a coherent optical system exploiting polarization multiplexing is discussed in this paper. The benefits of combining a phase estimation algorithm with a decision directed least-mean-square equalizer in a feedback configuration is reported.**

***Index Terms*—Coherent Systemns, Feedforward phase estimation, Wiener filtering, Kalman filtering.**

I. Introduction

COHERENT optical communications have gained renewed interest due to the availability of high speed digital signal processing, low priced components as well as partly relaxed receiver requirements at high data rates. When the outputs of a coherent homodyne receiver are sampled at the Nyquist rate, the digitized waveform contains full information of the electric field, preserving the amplitude, phase and polarization from the optical domain to the electrical domain, enabling new potential of multi-level signaling (M-ary PSK and M-ary QAM modulation), as well as the possibility of exploring polarization multiplexing. Additionally, it enables quasi-exact compensation of linear transmission impairments (CD and PMD) by a linear filter [1], which can operate adaptively to overcome time-varying impairments. Furthermore, in order to avoid the difficulties associated with the OPLL, carrier synchronization can be done in the DSP, by digital phase estimation techniques, allowing for a free running LO. Equalizers can achieve adaptation of their coefficients either by transmitting a training sequence, known symbol statistics or decision-directed (DD) adaptation. When no training sequence is transmitted (blind equalization), the constant modulus algorithm (CMA) introduced by Godard and Treichler is the most used, essentially because of its robustness and ability to converge prior to phase recovery [2]. In order to cope with laser phase noise, an elegant solution consists in using the CMA for initial adaptation, avoiding training sequences and enabling subsequent independent carrier phase estimation. Once equalizer convergence has been achieved, the equalizer switches to DD mode, whereby the error signal is derived from the error between the baseband signal and the nearest, ideal point of the constellation, improving the demodulator SNR performance [2]. In this paper we assess the performance of a coherent optical system employing a phase estimation algorithm combined with the equalizer in a feedback configuration.

Although this concept has been suggested in [1],[2] a detailed study of the performance improvement has never been done. The actual simulation of the 16-AQM coherent optical system was carried out in MATLAB. The paper is organized as follows: in section II the simulation model is described, section III presents the proposed algorithm and in section IV we present and discuss the simulation results; finally the conclusions are given in section V.

II. Simulation Model

A. Model description

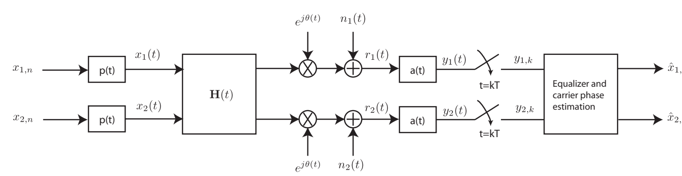

Fig. 1. System canonical model

The figure above represents the canonical model of a coherent optical system employing polarization multiplexing. The matrix $H(t)$ represents the fiber impulse response, completely describing a dually polarized channel. The frequency response of the fiber can be described by:

$$H(w) = T(w) \times e^{-\frac{1}{2}\beta_2 L w^2} \tag{1}$$

Where $T(w)$ is the fiber Jones Matrix accounting for PMD [3], β_2 is the Group Velocity Dispersion (GVD) parameter and L is the fiber length. Chromatic dispersion is accounted up to second order. Then, the signal is noise loaded, with both AWGN noise and phase noise. Phase noise is usually characterized as a Wiener process (ramdom walk). The sampling occurs at a rate of 2 samples per symbol, which was previously shown to be sufficient [4]. Linear equalization follows, by performing convolution with a bank of four complex valued T/2 spaced FIR filters, arranged in a butterfly structure. The linear equalizer calculates the minimum-mean-squared-error (MMSE) estimate of the k-th symbol $\tilde{x}_k$. The optimum solution for the coefficients is obtainable by the Wiener-Hopf equation [4]. However, in practice, H is time-varying due to PMD, and an adaptive equalizer is necessary. Therefore, the

This work was supported in part by "Fundação para a Ciência e Tecnologia" (FCT) under the programme POCTI/FEDER with grant REEQ/1272/EEI/2005 - Fibre Optic Supported Broadband Communication Networks.

L. M. Pessoa and H. M. Salgado are with INESC Porto, Faculdade de Engenharia, Universidade do Porto, Porto, Portugal (email: luis.pessoa@ieee.org, h.salgado@ieee.org).

I. Darwazeh is with the Department of Electronic and Electrical Engineering, University College London, U.K. (email: i.darwazeh@ee.ucl.ac.uk)

L. M. Pessoa also acknowledges support from a PhD grant from FCT

least mean square (LMS) or the recursive least squares (RLS) algorithms can be used to update the coefficients, and track the time varying minimum of the cost function.

III. Proposed Algorithm

The presented algorithm is an improvement over the one proposed in [5], wherein we calculate the phase estimate by using a generalization of the Wiener filter, the Kalman filter. For the case of zero delay these two filters can be shown to be equivalent. The estimated phase is given by the Kalman recursion:

$$\begin{aligned} \tilde{\theta}_{k+1} &= \tilde{\theta}_k + G \cdot (\psi_k - \tilde{\theta}_k) && (2) \\ &= \tilde{\theta}_k + (1-\alpha) \cdot \mathrm{angle}(\tilde{x}_k e^{-j\tilde{\theta}_k} \cdot \mathrm{conj}(d_{ref})) && (3) \end{aligned}$$

where $\alpha = (1 + r/2) - \sqrt{(1 + r/2)^2 - 1}$ and $r = \sigma_p^2/\sigma_{n'}^2$. σ_p^2 is the variance of the phase noise and $\sigma_{n'}^2$ is the variance of the phase associated with Gaussian noise. Therefore, the ratio of phase noise to the phase of amplitude noise r, determines the rate of decay of the filter exponential (forgetting factor).

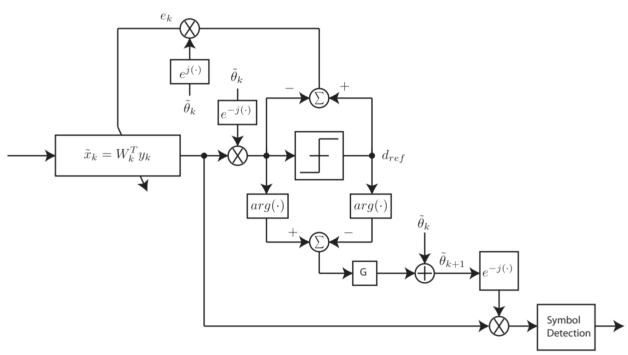

Fig. 2. Diagram of the equalizer and subsequent carrier phase estimation

In Fig. 2, the error signal for the equalizer is derived after carrier "de-spin", so that the equalizer output is still a constellation with ringed shape. Instead of determining the soft estimate ψ_k [5], here we follow the approach in [6], where the difference $\psi_k - \tilde{\theta}_k$ is calculated directly without the need to perform phase unwrapping.

IV. Results

In our numerical simulations, we have used a pulse shape $p(t)$, obtained by passing an ideal rectangular pulse train by a 5th order low pass Bessel filter with a 3-dB bandwidth of 80% of the symbol-rate. For the anti-alias (AA) filters $a(t)$, 3rd order low pass Bessel filters were used. In Fig. 3, we have plotted the symbol error rate versus input SNR per symbol. The SNR is defined as: $SNR = \frac{P_x T_s}{N_0} = \frac{E_s}{N_0}$ where P_x is the mean symbol power, E_s is the symbol energy and N_0 is the noise power spectral density. The bottom curve is the theoretical result, which only depends on the constellation type. The MMSE curve was obtained by calculating the optimum 13-tap set of coefficients in the MMSE sense that maximizes the output SNR [4] in the presence of an ideal channel, whilst considering the Bessel filters in both transmitter and receiver. All other results also consider these filters and were obtained by 13-tap adaptive filters (step size $\mu = 1 \times 10^{-3}$), with Monte-Carlo simulations and evaluated after convergence. As expected, the LMS curve represented by "$*$" closely matches the MMSE result. In the following group of three curves, we have employed the proposed algorithm whilst considering 300 kHz of phase noise combined linewidth. The curve represented by the circles symbol is for the case where the Wiener filter is used within the loop. From these results it can be seen that the Kalman filter outperforms the Wiener. The third curve shows the combined impact of CD ($D_0 = 4 \times 10^3$ ps/nm), PMD (mean DGD of 42 ps) and phase noise. It is very clear that decision-directed operation in feedback with carrier phase estimation clearly outperforms algorithms based on non-decision aided cost functions (CMA).

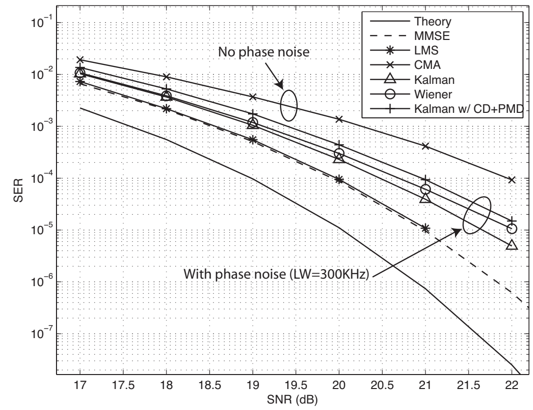

Fig. 3. Symbol error rate versus SNR.

V. Conclusions and Future Work

We have investigated in detail the implementation of digital signal processing algorithms in order to mitigate system impairments such as CD, PMD and laser phase noise, in a coherent system. We have shown the advantages of combining a Decision Directed equalizer with a carrier phase estimation stage in feedback. The Kalman filter is more suitable to operate in this condition than a Wiener filter, and lends itself to a much more efficient practical implementation. Work is under way to explore different issues concerning a parallel digital signal processor implementation, possibly in a FPGA system.

References

[1] E. Ip, A. Lau, D. Barros and J. M. Kahn, "Coherent Detection in Optical Fiber Systems", Optics Express, vol. 16, no. 2, pp. 753-791, Jan. 2008
[2] J. R. Treicheler, "Practical Blind Demodulators for High-Order QAM Signals", Proceedings of the IEEE, Vol 86, No 10, October 1998.
[3] A. Dal Forno, et al., "Experimental and theoretical modeling of polarization-modedispersion in single-mode fibers," IEEE Photon. Technol. Lett., vol.12, no. 3, pp. 296-298, 2000.
[4] E. Ip and J. M. Kahn, "Digital Equalization of Chromatic Dispersion and Polarization Mode Dispersion", JLT, pp. 2033-2043, Aug. 2007.
[5] E. Ip and J. M. Kahn, "Feedforward Carrier Recovery for Coherent Optical Communications", JLT, vol. 25, no. 9, pp. 2675-2692, Sep. 2007.
[6] Liang Zhao, Won Namgoong, "A novel phase-noise compensation scheme for communication receivers". IEEE Transactions on Communications 54(3): 532-542 (2006).