Assessment of Parallel Equalizer/Phase Estimation Algorithms in Coherent Optical Systems

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

***Abstract*—The options to implement a coherent optical system employing a phase estimation algorithm combined with adaptive linear equalization are investigated. Several carrier phase estimator strategies are discussed, in terms of parallelization, performance and implementation complexity.**

***Index Terms*—Coherent Systems, Feedforward phase estimation, Wiener filtering, Parallel algorithms.**

I. Introduction

COHERENT optical communications have gained renewed interest due to the availability of high speed digital signal processing. Additionally, it enables quasi-exact compensation of linear transmission impairments by a linear filter [1]. Furthermore, in order to avoid the difficulties associated with the optical phase locked loop (PLL), carrier synchronization can be done through digital phase estimation techniques, allowing for a free running local oscillator (LO), while tolerating 50% to 100% wider laser linewidth than PLL [2].

Considering equalization algorithms, when no training sequence is transmitted (blind equalization), the constant modulus algorithm (CMA) is the most used, essentially because of its robustness and ability to converge prior to phase recovery [3]. 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 CPE. Once equalizer convergence has been achieved, there is benefit in switching to decision directed (DD) mode, driven from symbol decision errors, improving the SNR (Signal to Noise Ratio) performance [3]. However, at this point, the equalizer might fail tracking the signal phase noise, if its impact is not residual. Therefore the phase must be estimated and its value considered in the error signal, precluding the use of independent CPE. Additionally, the decision feedback might be critical in high-speed parallelized DSP. In this paper we assess the performance of a phase estimation algorithm combined with a DD equalizer in a feedback configuration and compare it to the approach consisting of CMA followed by CPE, both for series and parallel implementations. Then we conclude which approach to take if parallelization is required.

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A recent work [1] suggests the integration of an adaptive digital equalizer with carrier synchronization using decision feedback. Although this concept has been suggested in [1],[3] a detailed study on the algorithms performance has never been done, specially taking parallelization into account. The actual simulation of the 16-QAM coherent optical system was carried out in MATLAB.

The paper is organized as follows: in section II the simulation model is described with focus on CPE issues, in section III we present and discuss the simulation results; finally the conclusions are given in section IV.

II. Simulation Model

A. Model description

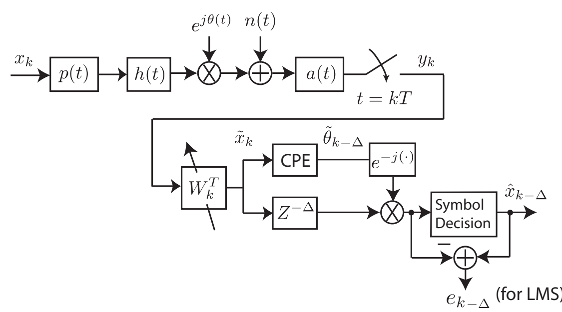

Fig. 1. System canonical model

Figure 1 represents the canonical model of a single polarization coherent optical system, where $p(t)$ is the pulse shape and $h(t)$ represents the fiber impulse response, which might include the effects of dispersion. The signal is noise loaded, with both phase noise $\theta(t)$ and AWGN noise $n(t)$. Phase noise is usually characterized as a Wiener process, being modeled as in [2]. The sampling occurs at a rate of 2 samples per symbol, which has been widely used in the literature [4]. Then linear equalization is performed through a convolution with a complex valued T/2 spaced FIR filter (W_k).

The linear equalizer calculates $\tilde{x}_k$, the estimate of the k-th transmitted symbol x_k, with its coefficients being adapted with a well-known algorithm, the least-mean squares (LMS). The fiber link might be time-varying, which originates the need for adaptive operation. After equalization, the CPE block has the goal of obtaining $\tilde{\theta}_k$, an estimate of θ_k, which will allow de-rotation of the signal by multiplying it with $e^{-j\tilde{\theta}_k}$, followed by a symbol-by-symbol detector to find $\tilde{x}_k$, the estimate of x_k. The CPE process operates in two steps. First a

soft estimate is obtained, which is the phase of $\tilde{x}_k$ referenced to the phase of x_k, after which the optimum Wiener filter is applied, consisting of two exponentially decaying sequences, causal and anti-causal [2], having an inherent delay of half the filter length. The soft estimate can be obtained either through DD or NDA (Non-Decision Aided, known as M^{th} power) approaches. However, for 16-QAM NDA, the mid amplitude symbols can not contribute to the estimate because of the irregular phase spacing, where the remaining symbols, called Class I by [5], are used. However, this has only been done for the simple running average filter. In the following sections, the performance for the Wiener filter is also discussed.

III. Results

In the considered case of combined DD equalization and CPE, we have found through simulation that the delay of the Wiener filter should be zero for optimum performance, because of the phase feedback to the equalizer. In practice, having a small finite delay would not significantly compromise the performance, provided the channel variations (due to time-varying impairments) are slow. The zero-delay Wiener filter can be implemented recursively (Infinite Impulse Response - IIR) which decreases computational complexity. However, recursive filters are sensitive to both parallelization and quantization issues. In Fig. 2 (a) we show that at least 8 bits are required in order to avoid performance degradation above 2dB stemming from fixed point quantization.

The discussed algorithms should be implemented with a high degree of parallelism, otherwise we are unable to implement them in real-time with the currently available technology. The recursive algorithm might be modified to accomplish this, with a look ahead computation [6] to refer the feedback to a result obtained L symbols before, at the expense of extra feedforward (FF) taps, without compromising performance. Fig. 2 (b) compares the BER performance versus linewidth per bitrate of different phase estimation algorithms. A non-Gray differential bit encoding scheme (proposed in [2]) was employed in all cases, preventing catastrophic bit error propagation (cycle slips) when phase noise is high. It is clear that the running average filter using NDA is not as optimized as Wiener approaches. The DD approach with $L = 32$ is always worse than NDA, which shows that DD is not well suited for parallelization due to feedback within the CPE block, opposed to NDA approach which might be parallelizable with no loss since it involves no feedback.

Fig. 3 compares the performance of several scenarios involving both equalization and phase estimation, including a 3rd order low pass Bessel filter for the pulse shape $p(t)$ and anti-alias (AA) filter $a(t)$. If no parallelization is required the LMS+DD approach should be chosen. If a parallelization level $L \leqslant 32$ is necessary, the LMS+ANDA approach is preferable, but if the requirement is greater than 32, then CMA+ANDA is the best option, because its performance does not depend on L. Furthermore, in the latter, provided FF taps are used already, these can be computed to belong to the filter anti-causal tail, improving the estimator accuracy.

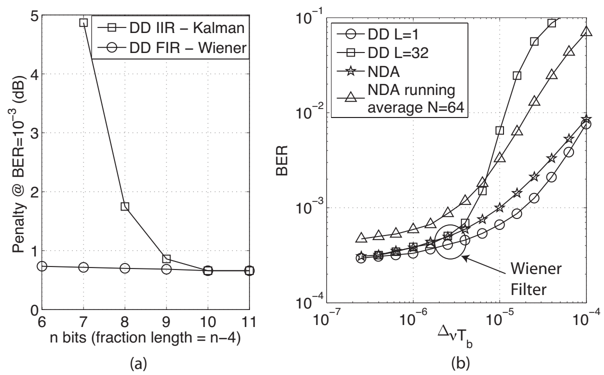

Fig. 2. (a) Penalty for a target BER=1e-3. $\Delta\nu T_b = 10^{-5}$. (b) Bit error rate versus laser linewidth per bitrate. $Eb/N0$ of 12dB (1dB above the differential AWGN limit BER $= 1 \times 10^{-3}$)

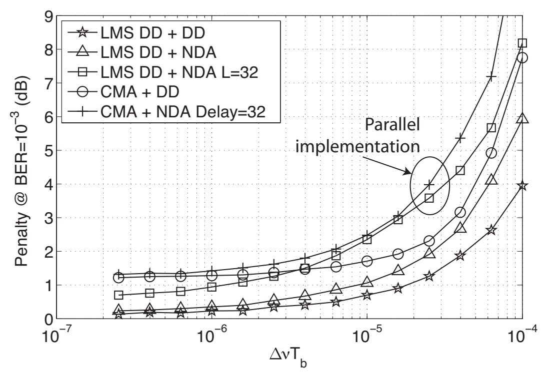

Fig. 3. Penalty versus laser linewidth per bitrate. Reference E_b/N_0 of 12dB (BER $= 1 \times 10^{-3}$ sensitivity point for LMS). The legend notation corresponds to "Equalizer"+"Phase Estimation Filter". FIR filters were used.

IV. Conclusions

The performance of a phase estimation algorithm operating in feedback with a LMS-DD equalizer in coherent optical systems was assessed, both for DD and NDA phase estimates. Its performance was compared to the CMA having separate CPE. Parallelization issues were also addressed. It was found that up to $L = 32$ the LMD-DD using feedback still overperforms the equivalent CMA approach, while having similar computational complexity levels.

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