Adaptive Electrical Equalization of Optical Impairments in Coherent Optical Systems

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

***Abstract*— This paper describes a coherent optical communication system, using differential quadrature phase shift keying (DQPSK). Impairments mitigation has greater potential in these systems because of the linear conversion from the optical to the electrical domain, specially when polarization multiplexing is explored as a means of increasing spectral efficiency [1]. We also discuss the interface between the homodyne IQ-receiver and the digital signal processor (DSP). Additionally, the system performance under severe distortions is investigated through simulations.**

***Index Terms*— Coherent Systemns, Homodyne Detection, Chromatic Dispersion Compensation, Polarization Mode Dispersion Compensation**

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. Coherent detection allows the optical field parameters (amplitude, phase, frequency and polarization) to be available in 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 [2]. Therefore we can reduce the symbol rate while keeping the bit rate, increasing the spectral efficiency and easing the complexity of A/D circuits used in demodulation/compensation schemes.

Dispersion compensation on IM/DD systems is not very efficient due to the non-linear optical to electrical (O/E) conversion in the photodiode, with loss of phase information. However, single side band (SSB) transmission allows the square law detection to largely preserve the phase. Moreover, maximum likelihood sequence estimation (MLSE) is the most effective means of impairments mitigation in these systems [3].

In contrast to IM/DD systems, complete equalization of chromatic and polarization mode dispersion (CD and PMD) is possible in coherent systems, in the electrical domain, as the equalizer operates on signals proportional to the electric field. Additionally, zero penalty dispersion compensation may also be achieved in the optical domain. However, adaptive schemes are rather complicated because the error signal is obtained after square-law detection in the photodiode [3].

Considering coherent receiver implementation, homodyne receivers are superior to their heterodyne counterparts, and seem to be the choice for future networks. However, as they are sensitive to phase noise, an elegant technique called phase diversity emerged, but only applicable to 2-level modulation signals. Therefore, for higher order modulation signals, an optical phase locked loop (OPLL) is necessary, which nowadays is still very difficult to implement. A turnaround to this problem is possible using DPSK modulation, where the information is encoded by changes in phase from one symbol to the next, and differential detection, which consists in pair-wise comparison of sample phases, assuming the optical carrier phase varies much more slowly than the phase modulation. However, this detection scheme is less performing than synchronous detection [4], where the decoding of data is performed on the basis of comparison of consecutive quadrant numbers, but requiring that the phase of the signal is tracked. Thereafter, the option is to cope with phase noise through digital phase estimation, using a DSP to track the signal phase [2].

In this paper, we will focus on differential PSK (DPSK) as well as joint polarization DPSK (JPDPSK) modulation formats. Joint polarization takes advantage of the fact that the fiber can propagate two nearly degenerate modes, orthogonally polarized into the two principal axes of the fiber. However, due to birefringence, these two modes suffer different phase delays during propagation, leading to output pulse broadening (PMD) [5].

When polarization is not exploited by the transmission system to carry information, polarization diversity receivers may be used to cope with the random variations in the state of polarization of the received signal. On the other hand, when JPDPSK is used, the received signal must be treated as a four-dimensional vector, allowing the equalizer to compensate high order PMD as well as CD and polarization dependent loss.

This paper presents our developments relating to the MATLAB simulation of a coherent optical system, and associated algorithms for mitigation of CD and PMD.

II. Transmitter

The transmitter consists of electrical driving circuitry (level generator and modulator driver) and the optical IQ-modulator. The light of a continuous wave (CW) laser is split between two arms, and one of them is $90°$ phase shifted. The orthogonal

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carriers are then modulated by Mach-Zehnder-Modulators (MZM), biased at minimum transmission, and driven by bipolar RF signals. As depicted in Figure 1, the optical transmitter is composed by one or two IQ-modulators, depending on whether we exploit polarization to carry information or not.

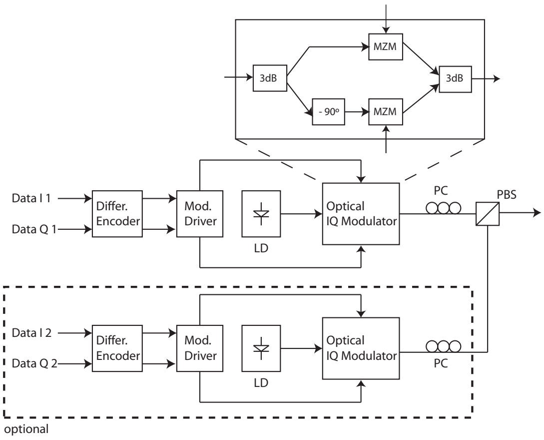

Fig. 1. Schematic of a multi-level coherent optical transmission system, optionally employing polarization multiplexing; LD: Laser Diode, PC: Polarization Controller, PBS: Polarization Beam Splitter.

The optical IQ-Modulator shown is the conventional structure to generate multi-level optical modulation signals. An optical DQPSK signal is generated by the transmitter, with the differential pre-coding executed according to the work of Griffin *et al* [6]. After the transmitter the signal is launched into the transmission channel, composed by an optical fiber which introduces chromatic dispersion and polarization mode dispersion, as well as attenuation. An optical amplifier compensates for attenuation, introducing amplified spontaneous emission (ASE) noise.

III. Homodyne IQ Receiver

The optical multi-level modulation signal can be detected by an homodyne IQ-receiver (Figure 2), whose general configuration is valid for any M-PSK and M-QAM modulation format. Coherent detection involves beating the incoming signal with light from a local oscillator (LO) laser [7], of near-identical wavelength and similar state of polarization (SOP), generating a photocurrent in the detector that corresponds to the beat product of the two lightwaves. Figure 2 shows how the signal is mixed with the LO in a phase/polarization diverse hybrid. We can see that no polarization controllers are present, due to the polarization diversity configuration, where both signal and LO waves are separated by polarization beam splitters (PBS) into orthogonal components, and each of these goes into a separate phase diverse combining stage.

The equations that follow will give a mathematical support to the previous explanation. In these, we consider only one phase diverse hybrid and assume that the signal is aligned in SOP with the LO in that hybrid. The complex envelope of the incoming optical multi-level modulation signal, and local

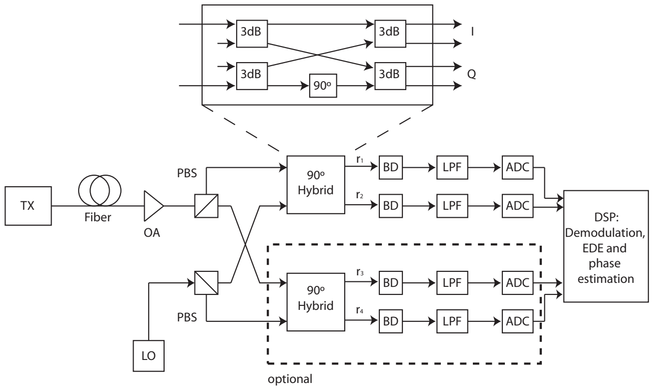

Fig. 2. Schematic of the whole system; TX: Transmitter, OA: Optical Amplifier, LO: Local Oscillator, BD: Balanced Detector, LPF: Low Pass Filter, ADC: Analogue to Digital Converter, DSP: Digital Signal Processor, EDE: Electronic Dispersion Compensation

oscillator laser are

$$\begin{aligned} E_S(t) &= a(t)\cdot e^{j\phi(t)}\cdot\sqrt{P_S}\cdot e^{w_S t+\phi_S+\phi_{NS}} = \\ &= [I(t)+jQ(t)]\cdot\sqrt{\frac{P_S}{2}}\cdot e^{w_S t+\phi_S+\phi_{NS}} = \\ &= E_I(t)+jE_Q(t); \end{aligned} \quad (1)$$

$$E_{LO} = \sqrt{P_{LO}}\cdot e^{w_{LO}t+\phi_{LO}+\phi_{NLO}} \quad (2)$$

where w_S and w_{LO} are the angular frequencies of the signal optical carrier and local oscillator, P_S and P_{LO} the CW power, ϕ_S and ϕ_{LO} initial phases, and ϕ_{NS} and ϕ_{NLO} the phase noise of the signal and LO lasers. $I(t)$ and $Q(t)$ are the in-phase and quadrature components of the transmitted complex envelope, and $a(t)$ and $\phi(t)$ its magnitude and phase. The signal wave and the LO wave combine in an optical 2×4 $90°$-hybrid, yielding 4 output fields. The electric field components (EFCs) at the output of the hybrids are detected by means of balanced photodiodes, which has the advantage of suppressing the relative intensity noise (RIN) [3]. The in-phase and quadrature photocurrents are

$$I^*(t) = \gamma\cdot(I(t)\cdot\cos(\Delta\phi)+Q(t)\cdot\sin(\Delta\phi)) \quad (3)$$

$$Q^*(t) = \gamma\cdot(-I(t)\cdot\sin(\Delta\phi)+Q(t)\cdot\cos(\Delta\phi)) \quad (4)$$

with $\gamma = R\cdot\sqrt{P_{LO}P_S/2}$, when neglecting shot noise. In the above equations, R is the responsivity of the photodiodes, and $\Delta\phi$ is the phase error due to frequency offset, phase offset and laser phase noise, which is given by

$$\Delta\phi(t) = (w_S - w_{LO})t + (\phi_S - \phi_{LO}) + (\phi_{NS} - \phi_{NLO}) \quad (5)$$

Therefore, in order to extract the modulation information the total phase error must be controlled. Moreover, for zero phase error, the in-phase and quadrature components of the transmitted complex envelope are obtained separately in the two arms. Signals r_1 and r_2 are the in-phase and quadrature components of the received EFC $\hat{E}_x(t)$, like r_3 and r_4 are for the EFC $\hat{E}_y(t)$. These signals are then sampled, with a

sampling interval of one half the symbol period ($T_S/2$), to allow the employment of a T/2 fractionally spaced equalizer (FSE) in the digital domain, which is optimum for coherent receivers [8]. The low pass filters preceding the ADCs, are supposed to simulate their low pass characteristic.

IV. DSP FOR DEMODULATION AND COMPENSATION OF OPTICAL IMPAIRMENTS

In the more complex case of 4 sampled signals (polarization diversity), compensation of impairments is performed by a bank of 4 complex valued T/2 spaced FIR filters, working on the in-phase and quadrature components of each received polarization, arranged in a butterfly structure [3] and optimized using an LMS algorithm. When phase noise is present in the signal, the equalizer needs a means of estimation of the signal phase in order that the algorithm to achieves convergence. This can be done with a simple phase estimation algorithm [3]. However, if the constant modulus algorithm (CMA) is used instead of LMS, no algorithm is necessary to achieve convergence in the equalizer. In the last case, other more sophisticated algorithms may be used after the equalizer to estimate the signal phase such as those referred in [9] and [10], for QPSK, and [2] for 16-QAM modulation formats.

V. TRANSMISSION CHANNEL MODEL

The fiber transfer function can be modeled according to Francia *et al* paper [5], neglecting polarization dependent loss

$$T(w) = e^{-\alpha L} e^{-j\beta(w)L} M(w) \tag{6}$$

where $\beta(w) = (\beta_x(w) + \beta_y(w))/2$ is the fiber mean propagation constant, obtained by averaging the propagation constants of the two principal states of polarization (PSPs), α is the fiber attenuation coefficient (assumed to be 0 in this paper), L is the fiber length and $M(w)$ is the unitary matrix

$$M(w) = \begin{bmatrix} u_1(w) & u_2(w) \\ -u_2^*(w) & u_1^*(w) \end{bmatrix} \tag{7}$$

and $|u_1(w)|^2 + |u_2(w)|^2 = 1$. Chromatic dispersion is accounted up to second order. The PMD emulator is built in the time domain and uses six delay times to model the response of first and second order PMD. The first order PMD is given by the $\mathrm{DGD} = \Delta\tau$, while the second order parameters are the Polarization Chromatic Dispersion (PCD), which represents the frequency dependence of the DGD, and the depolarization rate, which represents the frequency dependence of the principal axes of polarization. The PCD and depolarization rate values were obtained from the mean DGD using the equations from Nelson *et al* [11].

VI. SIMULATION RESULTS

In this section we will analyze the impact of several parameters on the digital algorithm, like the number of filter taps, different low-pass filter configurations, as well as the system performance under severe PMD and CD distortions.

We have conducted two major groups of simulations. In the first group we have used ideal analogue to digital conversion (ADC), so no filtering is performed before the signal digitation. In the second group, we have investigated the equalizer performance with different ADC filter bandwidths. The dispersion coefficient of the single mode fiber (SMF) is assumed to be $20\ ps/(\mathrm{nm} \cdot \mathrm{km})$. The transmitted pulse shape has an unchirped Gaussian envelope $e^{-t^2/2T_0^2}$, with $T_0 = 36$ps [3]. The transmission rate was 10 Gsymbols/s in each polarization. Phase noise was not considered.

Concerning ideal ADC, in Figure 3, one can observe two sets of curves. While squares refer to equalization using coefficients that were obtained by calculating the optimum filter coefficients that invert exactly the fiber transfer function, circles refer to coefficients that have been determined adaptively, and thus they can improve even the back-to-back performance. It is clear that the number of filter taps used has critical importance when the link distance increases. For short link distances, the adaptive filter with 61 taps has poorer performance than the one with 13 taps, due to the excessive number of taps, resulting in noisy estimates for the parts of the impulse response with near zero energy. A signal to noise ratio (SNR) per bit of 8 dB was used, a step of 0.01 for the adaptive algorithm, and fiber PMD was set to zero.

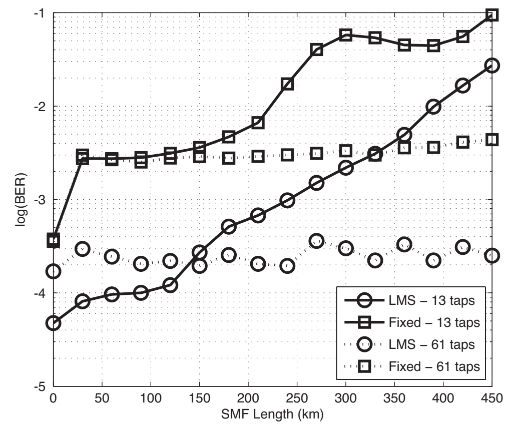

Fig. 3. Bit error rate versus single mode fiber length for fixed and adaptive filter coefficients, with varying number of taps

A plot of the bit error rate versus SNR per bit for a link distance of 300 km is shown in figure 4, where the coefficients were obtained adaptively. It is clear that the higher the SNR, the more difficult it is for the equalizer to follow the theoretical curve, which is even more evident for a lower number of taps.

The results that follow intend to show the impact of non-ideal ADC response in the equalizer performance. Figure 5 shows that a filter with a reduced bandwidth gives better results, for the whole range of distances considered in the case of fixed coefficients, and specially for higher distances in the case of adaptively determined coefficients. The SNR was set deliberately high at 17dB per bit.

The filters used for ADC low bandwidth simulations, are bessel filters of third order. The use of a lower bandwidth filter increases the energy at the sample-times, but also increases the inter symbolic interference (ISI), which must be compensated by the FIR equalizer [12].

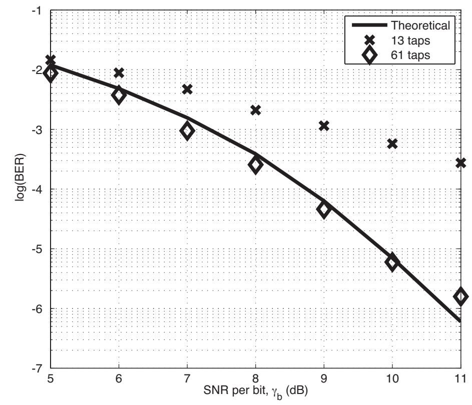

Fig. 4. Bit error rate versus signal to noise ratio per bit, with varying number of taps

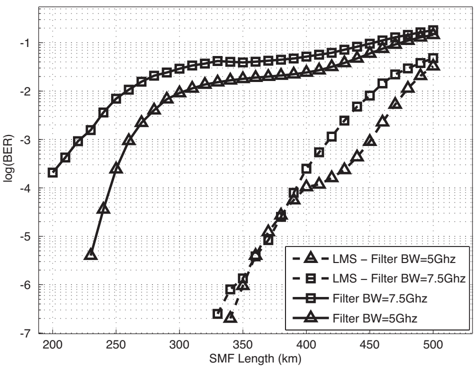

Fig. 5. Bit error rate versus fiber length for both fixed and adaptively determined coefficients, for 2 different filter configurations

In order to investigate the effect of PMD plus CD in the system performance, a simulation was carried out. The result is shown in figure 6. The impact of PMD increases with the

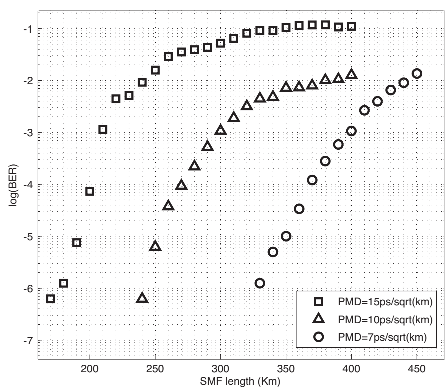

Fig. 6. Bit error rate versus fiber length for 3 different levels of induced PMD, and with a fixed dispersion coefficient

square root of the distance. We can see that a BER of 10^{-6} is achievable for a link distance of 330 km and a PMD coefficient of 7 $\mathrm{ps}/\sqrt{\mathrm{km}}$. The typical PMD of a commercial fiber is in the order of $0.1\mathrm{ps}/\sqrt{\mathrm{km}}$ or less, so the values simulated are for worst scenario conditions. The biggest advantage of the PMD fiber model we used is the fact that it is deterministic, allowing us to simulate very rare events. In reality, the DGD has a Maxwellian probability distribution, therefore, those rare events where the DGD is significantly larger than its mean are particularly important, since they are the ones most likely to result in system outages [13].

VII. Conclusions and Future Work

We have investigated a coherent optical system, detailing the transmitter and receiver implementation, fiber model with CD and PMD emulation, and the digital signal processing necessary for impairments compensation and demodulation. We have shown the advantages of coherent systems, in terms of spectral efficiency, possibility of polarization multiplexing and enhanced possibilities for dispersion compensation. In terms of future work, the main topics consist in exploring different transmitter configurations, assess the effect of phase noise when PMD is present, as well as investigate the issues of a parallel digital signal processor implementation.

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