Quadrature Imbalance Compensation for PDM QPSK Coherent Optical Systems

Constantinos S. Petrou, Athanasios Vgenis, Ioannis Roudas, and Lampros Raptis

***Abstract*—In this letter, we study the impact of quadrature imbalance (QI) on the performance of optical communications systems using polarization-division-multiplexed (PDM) quadrature phase-shift keying (QPSK), with coherent detection and digital signal processing. We compare, via simulation, the performance of three QI compensation algorithms, suitable for PDM QPSK coherent optical receivers, including a novel, blind, adaptive, constrained equalizer, based on the constant modulus algorithm. We show that dedicated QI compensation is mandatory and cannot be substituted by conventional adaptive electronic equalizers designed for intersymbol interference mitigation.**

***Index Terms*—Coherent optical communications, quadrature imbalance (QI), quadrature phase-shift keying (QPSK).**

I. Introduction

COHERENT phase-diversity receivers suffer from quadrature imbalance (QI) [1], [2]. QI arises from imperfections of the 90° optical hybrid and from responsivity mismatches, in both balanced and single-ended photodetectors. QI causes DC offset, amplitude, and phase mismatch between the received signal quadratures. It is a ubiquitous effect, regardless of the hybrid type, that affects the performance of subsequent digital signal processing (DSP) algorithms at the receiver [3], [4]. Though large amounts of QI can be avoided by careful receiver design, aging, and equipment maladjustments will invariably introduce QI, justifying a dedicated compensation scheme. Various algorithms that address QI have been proposed in the optical communications literature [2]–[5].

In this letter, we investigate the joint effect of amplitude and phase mismatch on the performance of polarization-division-multiplexed (PDM) quadrature phase-shift keying (QPSK) systems. We show that QI can produce penalties routinely exceeding 3 dB if left unattended. We propose a novel, blind, adaptive QI compensation scheme, based on the constant modulus algorithm (CMA) [6], suitable for receivers operating with both symbol-spaced (R_S) and fractionally spaced $(2R_S)$ sampling. We study the robustness of the proposed QI compensator in the presence of amplified spontaneous emission (ASE) noise. Finally, we compare its performance with that of other QI compensation algorithms [3], [4], and conventional electronic equalizers [7]. We show that QI compensators are mandatory and cannot be substituted by equalizers designed for intersymbol interference (ISI) mitigation. We also show that some compensation schemes are only suitable for receivers with R_S sampling, e.g., [3], while the others should be subjected to optimization.

II. QI Equalization Schemes

Consider a PDM QPSK optical communications system employing a polarization- and phase-diversity coherent receiver. For simplicity, we assume no cross-polarization interference due to polarization rotations. The in-phase (I) and quadrature (Q) photocurrents at the output of each phase-diversity receiver, are

$$\mathbf{I} = [I_{ip}\cos(a(t)+\varepsilon) \quad I_{qp}\sin(a(t)-\delta)]^T \tag{1}$$

where I_{ip}, I_{qp} are the I/Q photocurrent amplitudes, $a(t) = 2\pi f_{\rm IF}t + \Delta\varphi_n(t) + \varphi_k$ is the instantaneous phase, $f_{\rm IF}$ is the intermediate frequency (IF) offset between the transmitter and local oscillator (LO) lasers, $\Delta\phi_n(t)$ is the difference between the laser phase noises, ϕ_k is the modulation phase during the kth symbol interval, ε, δ are phase deviations, and T denotes transposition. The total phase mismatch θ equals $\varepsilon + \delta$. In (1), we omitted the DC components of the photocurrents, the additive noise, and other transmission effects. After sampling at the symbol rate, (1) can be rewritten in matrix form, as $\mathbf{I} = \mathbf{M}\mathbf{I_Q}$, where $\mathbf{I} = [I[n] \quad Q[n]]^T$ is the received photocurrent vector, $\mathbf{I_Q} = [\cos a[n] \sin a[n]]^T$ is the desired quadrature component vector, and $\mathbf{M}$ is a 2×2 real mixing matrix, representing the effect of QI.

The proposed algorithm attempts to adaptively estimate $\mathbf{M}^{-1}$ using an iterative procedure, based on the CMA [6]. To facilitate convergence, we impose constraints on the elements of $\mathbf{M}^{-1}$ by writing it in the form

$$\mathbf{M}^{-1} = \begin{bmatrix} I_{ip}^{-1}\cos\delta & I_{qp}^{-1}\sin\varepsilon \\ I_{ip}^{-1}\sin\delta & I_{qp}^{-1}\cos\varepsilon \end{bmatrix}. \tag{2}$$

In the following, we refer to this compensator as constrained QI-CMA. The CMA is used to estimate the parameters $I_{ip}, I_{qp}, \varepsilon, \delta$, by minimizing the instantaneous cost function $\xi[n] = e^2[n]$, where $e[n] = \hat{\mathbf{I}}_{\mathbf{Q}}^{\mathbf{T}}[n]\cdot\hat{\mathbf{I}}_{\mathbf{Q}}[n] - R$ is the error function, hat ˆ denotes estimation, and R is the sum of the average optical signal and noise powers. We define the array of estimated parameters $\mathbf{Z}[n] = [\hat{I}_{ip}[n]\,\hat{I}_{qp}[n]\,\hat{\varepsilon}[n]\,\hat{\delta}[n]]^T$, and use the stochastic gradient algorithm for their update. The

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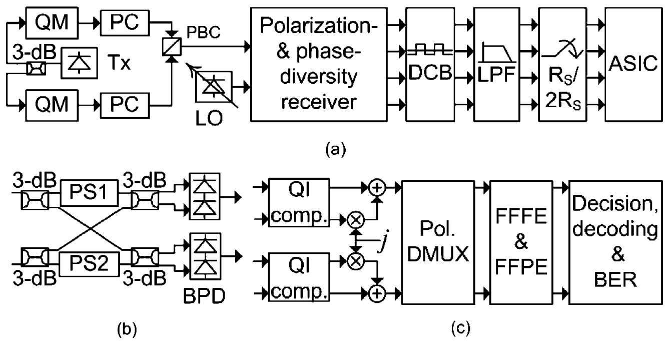

Fig. 1. System block diagram. (a) Transmitter and receiver. (b) Phase-diversity receiver. (c) ASIC.

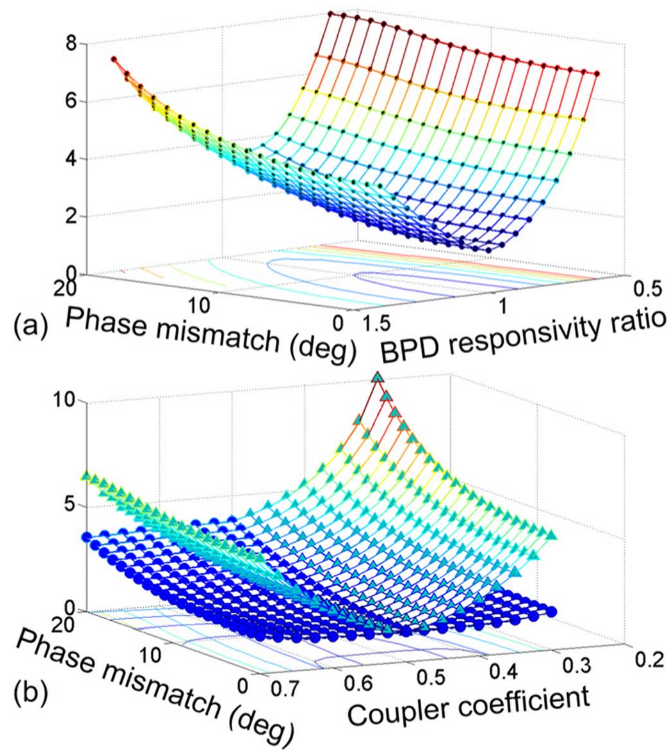

Fig. 2. OSNR penalty at $P_e = 10^{-9}$ for various settings of the optical hybrid and BPDs. (a) Combination of phase mismatch and BPD responsivity ratio deviation. (b) Combination of phase mismatch and coupling coefficient values (circles: nonideal output couplers; triangles: nonideal input couplers).

independently adjustable parameters can be further reduced, i.e., $\lambda = \sqrt{(I_{ip}/I_{qp})}\varepsilon = 0$, resulting in an additional penalty.

In [3], a geometric method for estimating the parameters of $\mathbf{M}^{-1}$ is used. Namely, the parameters λ, θ are obtained by fitting the constellation diagram of the quadrature photocurrents, given by (1), by an ellipse [8]. The ellipse parameters are then used to compute $\mathbf{M}^{-1}$. In contrast, [4] uses a Gram–Schmidt orthogonalization procedure, using a slightly different expression for $\mathbf{M}^{-1}$. Ensemble averaging is substituted by time averaging. Algorithm [5] is a special case of [4], assuming $\lambda = 1$, and will not be studied further here.

Polarization rotations induce mixing of the two PDM signals, causing the outputs of each phase-diversity receiver to contain interference terms, not included in (1). Symbol-spaced sampling results in constellations resembling concentric ellipses [Fig. 3(a)]. However, the effect of QI can still be described by a mixing matrix, since QI is a characteristic of each phase-diversity receiver and not of the received signal. All aforementioned algorithms are thus valid for symbol- and fractionally spaced sampling, without modification, apart from [3], which is not applicable in the latter case, since the received constellation has no longer an elliptical shape.

III. System Model

Fig. 1(a) shows a representative back-to-back coherent PDM QPSK system used for assessing the performance of the various QI compensation algorithms, via simulation. The optical signal from a laser diode is equally split and QPSK modulated in two parallel quadrature modulators (QMs). The two optical QPSK signals are superimposed with orthogonal states of polarization (SOPs), using two polarization controllers (PCs) and a polarization beam combiner (PBC), to form a PDM QPSK signal. An arbitrary polarization rotation creates cross-polarization interference. The receiver front-end is composed of a LO, two polarization beam splitters (PBSs) with aligned principal axes, and two phase-diversity receivers. Each of the latter employ a 2×4 90° optical hybrid and two balanced photodetectors (BPDs). Each hybrid [Fig. 1(b)] is comprised of four 3-dB couplers and two phase shifters (PSs) (with nominal values 0° and 90°, respectively). The photocurrent at the output of each of the four balanced detectors is passed through a DC block (DCB), a low-pass filter (LPF) with 3-dB bandwidth equal to 0.8 times the symbol rate R_S, and a sampler. Then, the samples are fed into an application specific integrated circuit (ASIC) for DSP. Sampling at both R_S and $2R_S$ is implemented. The ASIC block diagram is shown in Fig. 1(c). Initially, QI is separately estimated for each phase-diversity receiver. The quadrature samples are then combined into a complex sample, and polarization demultiplexing (POL DMUX) is performed [7]. Phase tracking is accomplished using feedforward frequency estimation (FFFE) [9] and feedforward phase estimation (FFPE) [10]. We choose $\Delta v/R_S = 0.5\ 10^{-3}, \Delta v$ being the total 3-dB laser linewidth, and the IF offset 0.05 R_S. The FFFE block size spans the whole simulation window and the FFPE block size is 10. Performance is evaluated using a semi-analytical method [11] for error probability $P_e = 10^{-9}$ (Fig. 2), and a Monte Carlo method, in the presence of ASE noise, estimating the bit-error rate (BER) over 100 000 bits (Fig. 3). The optical signal-to-noise ratio (OSNR) is measured at a resolution bandwidth of 1.25 R_S.

IV. Results and Discussion

Fig. 2 shows the OSNR penalty, for a single polarization tributary, calculated using the semi-analytical method, as a function of various settings of the optical hybrid and the BPDs, when no QI compensation is performed. Here, we assume that transmitted SOPs coincide with LO SOPs, corresponding to no polarization rotation, so the POL DMUX module is omitted. A number of combinations of ε and δ, each producing the same total phase mismatch θ were simulated, and the average penalty was found. Penalties can routinely exceed 3 dB, even for relatively small deviations from the nominal settings. Phase mismatch is the most influential impairment. Nonideal output

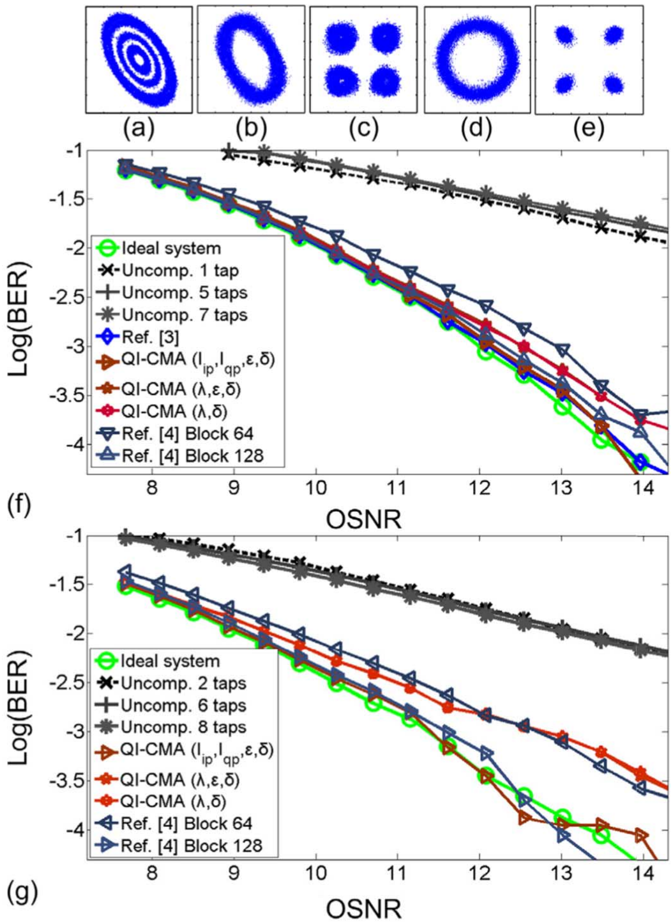

Fig. 3. Representative constellations: (a) input; (b), (d) at the output of the POL DMUX and (c), (e), after phase tracking, with, and without QI compensation, respectively, for a system with R_S sampling; (f), (g) BER versus OSNR for a system with R_S and $2R_S$ sampling, respectively. $R_S = 10$ GBd.

couplers affect performance less than nonideal input couplers. Compensation reduces the penalty below 0.3 dB in all cases.

Subsequently, we evaluate QI compensation algorithm performance in the presence of ASE noise. As a reference, an ideal receiver is considered, exhibiting no QI and using a rudimentary butterfly equalizer for POL DMUX, i.e., with 1 tap and 2 taps, for R_S and $2R_S$ sampling, respectively. QI is then introduced. Assuming a rather exaggerated worst-case scenario, we arbitrarily set the phase deviations to $\varepsilon = 0°$ and $\delta = \pm 30°$ for each receiver, respectively, the coupling coefficients of the 3-dB couplers to +30% of their nominal value, and the I/Q responsivity ratio deviation to +20%. Fig. 3(a)–(e) shows representative constellations at the input (a), the output of the POL DMUX [(b) (d)], and after phase tracking [(c) (e)], with, and without QI compensation, respectively, at 22-dB OSNR. Fig. 3(f), (g) shows plots of the BER versus OSNR for a variety of QI compensation options, with R_S and $2R_S$ sampling, respectively. Dotted curves correspond to the case where no dedicated QI compensation is performed. Although multitap butterfly equalizers are successful in mitigating ISI, they are inadequate for compensating large amounts of QI. They also exhibited extremely slow convergence, requiring as much as 20 000 symbols. This is attributed to the inability of the transverse filter at each butterfly branch to unravel the erroneous superposition of the two quadratures. In implementing [3], only 1000 samples are used for ellipse estimation. In implementing [4], time averaging over realizable block sizes is performed. A minimum block size is required. Decreasing the number of independently adjustable parameters of the constrained QI-CMA produces a penalty, significant in the case of $2R_S$ sampling. The CMA step size parameter is always optimized and found in the range 1–5 10^{-3}. All optimized algorithms exhibit almost identical, close to ideal performance, due to their similar operating principle, i.e., they are zero-forcing equalizers that differ only in the accuracy of the estimation of the mixing matrix.

V. Conclusion

We compared the performance of two previously proposed QI compensation schemes with that of a novel, blind, adaptive QI compensation algorithm. PDM QPSK systems operating with symbol-spaced and fractionally-spaced samples were studied. We conclude that QI can cause significant penalty and needs dedicated compensation to eliminate its impact, a function adaptive electronic equalizers cannot perform.

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