Impact of Receiver Imperfections on the Performance of Coherent Intradyne DQPSK Receivers

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Abstract: We theoretically investigate the impact of 90° optical hybrid and balanced detector imperfections on the performance of a coherent intradyne DQPSK system using feedforward frequency and phase estimation.

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1. Introduction

Recently, Differential Quadrature Phase Shift Keying (DQPSK) optical communication systems using coherent receivers with Digital Signal Processing (DSP) have been receiving considerable attention due to their superior sensitivity and spectral efficiency compared to binary On-Off-Keying (OOK) [1]. In addition, chromatic dispersion, polarization mode dispersion, phase noise and intermediate frequency offset can be compensated at the coherent DQPSK receiver using DSP algorithms [2–6].

In this paper, we study by simulation the impact of coherent intradyne DQPSK receiver imperfections on overall system performance. More specifically, we investigate the impact of 90° optical hybrid and responsivity mismatch of the photodetectors, which cause quadrature imbalance to the resulting photocurrents [7]. It is shown that the most important impairment is phase mismatch in the optical hybrid and that receiver imperfections can cause penalties larger than 3 dB under certain conditions.

2. System overview

The block diagram of the simulated DQPSK system with a coherent intradyne receiver, in a back-to-back configuration, is shown in Fig. 1. A Pseudo Random Binary Sequence (PRBS) is segmented into words of two bits and the corresponding decimal numbers are calculated. Inverse reflective Gray coding is used to map the decimal numbers n into modulation phases φ using the transformation $\varphi=n\pi/4$. The resulting phase sequence is differentially encoded and turned into a Non-Return-to-Zero (NRZ) complex symbol sequence of unit amplitude. The differentially encoded symbol sequence modulates the output of a CW laser. Symbol rate is half the original bit rate. The modulated optical field is mixed with the field of a local oscillator laser in a 2×4 90° optical hybrid, followed by a set of balanced detectors. The 90° hybrid is composed of four 3-dB couplers and two phase shifters [8]. Coupling coefficients a_i, associated to voltage controls VCi, i = 1-4, have a nominal value of 0.5. Phase shifters PS1 and PS2, associated to control voltages VCi, i = 5-6, shift the phase by ε and $90°+\delta$, respectively, while nominally $\varepsilon = \delta = 0°$. The photocurrents are passed through low pass filters (LPFs) and sampled with sampling frequency equal to the symbol rate. The sampled photocurrents are fed into a DSP unit, which uses feedforward algorithms for estimation and compensation of the intermediate frequency offset and the laser phase noise [2,3].

Due to the linearity of the coherent receiver, in the absence of phase noise, optical signal-to-noise ratio (OSNR) penalty can be accurately calculated through the eye opening at the output of the receiver using the relation Penalty (dB) = 20 log(eye back-to-back eye/output eye). In the presence of phase noise, Monte Carlo simulation of the phase noise alone and calculation of the penalty using the aforementioned relation yields fairly accurate results. For simplicity, we neglect polarization effects in the hybrid.

3. Simulation results

We simulate a system with a symbol rate $R_S = 1/T = 10$ GBd, LPF 3-dB bandwidth 0.8 R_S, $P_S = P_{LO} = 1$ mW and responsivity nominal values R = 0.9 A/W. In the presence of intermediate frequency offset alone, the constellation diagram after detection resembles a circle (Fig. 2a). In the presence of phase mismatch, which depends on $\varepsilon+\delta$, it resembles an ellipse rotated with respect to the axes (Fig. 2b). Non-ideal coupling coefficients cause amplitude mismatch, turning the constellation diagram into an ellipse whose semiaxes are aligned to the axes (Fig. 2c-e). Non-balanced detection causes amplitude mismatch and DC offset, translating the ellipse with respect to the origin (Fig. 2f). Simultaneous presence of all imperfections causes the constellation diagram to resemble an ellipse, rotated and translated with respect to the axes.

Fig. 3 shows the penalty, due to individual receiver imperfections, before the DSP circuit in the absence of phase noise. Phase mismatch causes a significant penalty even for small deviations of ε, δ and is by far the most detrimental impairment (Fig. 3a). For instance, erroneously setting $\varepsilon = 15°$ results in 3 dB penalty. Non-ideal

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splitting ratios of the incoming fields (due to erroneous setting of the control voltages VC1-2) affects both quadratures in the opposite sense (Fig. 3b) and yields unequal power levels at the hybrid outputs. Non-ideal coupling ratios at the hybrid output (control voltages VC3-4) further exacerbate the inequality of output power levels (Fig. 3c). Nevertheless, the penalty is small when phase shifting is performed correctly. For instance, a 20% deviation causes 1 dB penalty in the former case and less than 0.2 dB in the latter case. Responsivity imbalance in each detector also produces penalty (Fig. 3d) due to unequal photocurrent amplitudes.

Fig. 4 shows the combined effect of 3-dB laser linewidth and phase mismatch on the overall system performance, after DSP processing. Results for 100 combinations of ε and δ producing the same phase mismatch value are averaged. Average penalty for 15° mismatch is 1.8 dB. Many instances yield much larger penalties than 3 dB, even though the average penalty is below that.

4. Conclusions

Optical hybrid and balanced detector imperfections in a coherent intradyne DQPSK receiver lead to quadrature imbalance. Resulting photocurrents exhibit amplitude and phase mismatch and DC offsets affecting the performance of subsequent DSP circuits. The aforementioned impairments can cause penalties in excess of 3 dB.

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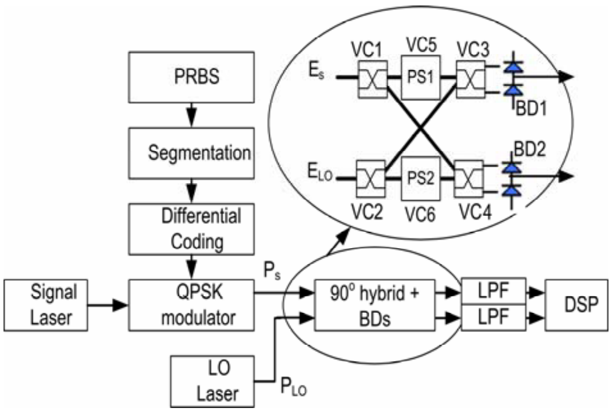

Fig.1 System block diagram (Symbols: P: Power, E: Electric field, S: Transmitted signal, LO: Local oscillator, VC: Voltage control, PS: Phase shifter, BD: Balanced detector, C1-C4: 3-dB couplers, C5-C6: Phase shifters).

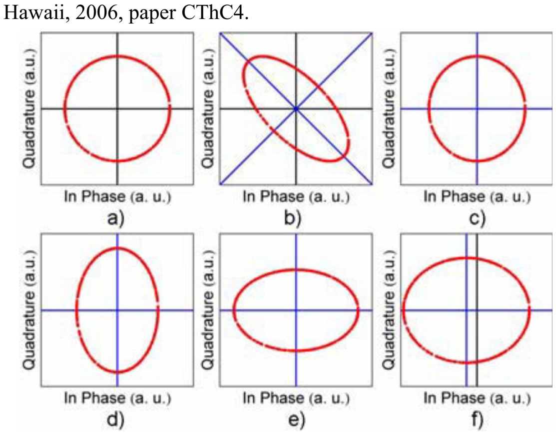

Fig. 2 Constellation diagrams after detection. a) Ideal system, b) With 40° phase mismatch, c) With deviation of output coupler coefficient, 40% (VC3 or 4), d) and e) With deviation of input coupler coefficient, 40% (VC1: Fig. 2d – VC2: Fig. 2e), f) Deviation of photodiode responsivity, 40%.

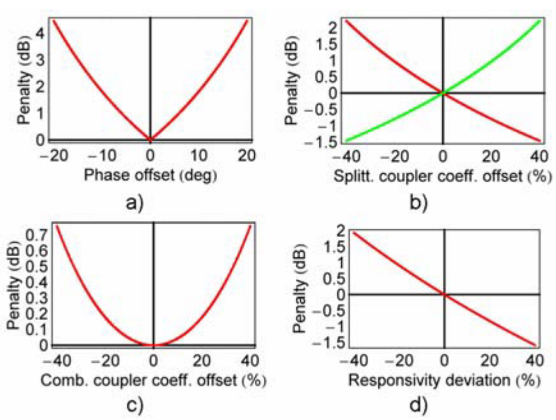

Fig.3 OSNR penalty for all possible 90° hybrid and balanced detector imperfections, immediately after detection.

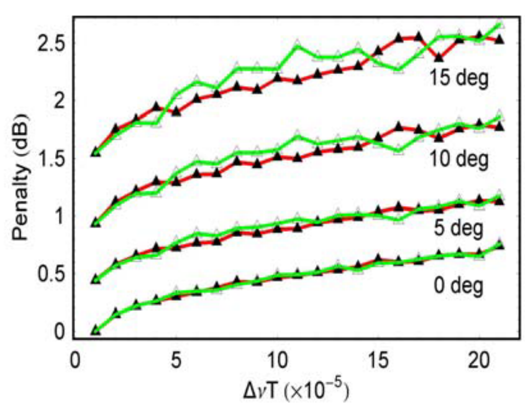

Fig.4 OSNR penalty vs total 3-dB linewidth–Symbol rate product, for various values of phase mismatch. Solid triangle: In-phase photocurrent. Open triangle: Quadrature photocurrent.