Compensation of coherent DQPSK receiver imperfections

I. Roudas (1, 2), M. Sauer (2), J. Hurley (2), Y. Mauro (2), and S. Raghavan (2)
(1) Dpt. of Electrical & Computer Engineering, University of Patras, Rio 26500, Greece; E-mail: roudas@ece.upatras.gr
(2) Corning Inc., Corning, NY 14831, USA.

Abstract: We experimentally demonstrate that optical hybrid imperfections and intermediate frequency offsets can seriously degrade the performance of coherent synchronous phase-diversity DQPSK receivers but can be compensated for by using digital signal processing.

Differential Quadrature Phase Shift Keying (DQPSK) is a promising modulation format for next-generation, long-haul optical communication systems due to its spectral efficiency and its resilience to fiber transmission impairments [1]. In principle, DQPSK receivers using coherent phase-diversity detection and feed-forward phase noise estimation [2], [3] can achieve superior sensitivity, selectivity and electronic compensation performance compared to their interferometric, direct-detection counterparts. However, in practice, phase-diversity receivers are vulnerable to imperfections of the optical hybrid, which result in DC offsets, and both amplitude and phase errors in the output photocurrents. This effect is called *quadrature imbalance* [4]. Moreover, the performance of the feed-forward phase noise estimation algorithm proposed by [2], [3] is deteriorated by even slight frequency misalignments of the transmitter and local oscillator lasers, which result in a nonzero intermediate frequency (i.e., *intermediate frequency offset*) [5]. Both effects were given little attention in the optical communications literature [6], [7]. Here, we experimentally study the impact of the aforementioned impairments on the performance of a coherent phase-diversity DQPSK receiver. We show that quadrature imbalance can be corrected by ellipse fitting and Gram-Schmidt-like orthogonalization. In addition, we show that intermediate frequency offset can be estimated using low complexity, feed-forward, least-square-error based algorithms.

Fig. 1 shows the block diagram of the experimental setup used for the study of the coherent phase-diversity DQPSK receiver. A CW optical signal from an external cavity laser (ECL) is externally DQPSK modulated using a quadrature modulator (QM) driven by two 0.1-2.5 Gb/s pseudo-random bit sequences (PRBS) taken from two output ports of a four channel pulse pattern generator. The optical signal passes through a variable optical attenuator (VOA) to emulate fiber transmission. The received optical signal and the light of a separate external cavity laser, acting as a local oscillator, are combined, in phase and in quadrature, using a 2×2 90 deg optical hybrid [8]. The optical hybrid is composed of four polarization controllers (PCTR), a polarization-independent 3-dB coupler (CPL), and two fiber polarizers (POL). The polarization controllers are adjusted in order to change the state of polarization of the optical signals at the input ports of the 3-dB coupler and the principal axes of the fiber polarizers, so that the coherent beating terms of the two output photocurrents are approximately 90 deg out of phase (i.e., quadratures). Two, approximately matched, fast photodiodes (PD) are used for the detection. Finally, a 2.5 GHz, 20 GSa/s real-time sampling oscilloscope (Tektronix TDS 7254 digital phosphor oscilloscope, DPO) samples the AC components of the photocurrents and stores the signal for further processing. An electrical spectrum analyzer is used for the fine adjustment of the carrier frequencies of the received signal and the local oscillator, so that the intermediate frequency lies in the range 50-500 MHz. For simplicity, no automatic frequency control (AFC) is used, since the carrier frequencies of the external cavity lasers are stable for the duration of a single measurement.

Fig. 2 shows the computer implementation of the digital signal processing (DSP) application-specific integrated circuit (ASIC). The inputs of the ASIC are the two sampled photocurrents corresponding to the two quadratures. The inputs are filtered to remove out-of-band shot and thermal noise. The resulting photocurrents are resampled once per symbol at the optimum sampling instant. Subsequently, the ASIC first estimates and corrects the quadrature imbalance. The two equalized quadratures are proportional to the real and imaginary parts of the complex electric field of the received optical signal, downshifted around a non-zero intermediate frequency. The ASIC then estimates and removes the intermediate frequency offset and the unwrapped phase noise. Finally, the signal space (i.e., constellation) diagram is plotted. In parallel, the same compensation procedures are applied to the original, densely sampled photocurrents for plotting eye diagrams (not shown).

Fig. 3(a) shows a parametric plot generated using the resampled photocurrents corresponding to the two quadratures as XY axes (points). The elliptical shape indicates that the two quadratures have unequal amplitudes and a phase difference less than 90 deg [6], due to the maladjustment of the paddles of the polarization controllers of the optical hybrid, the imperfect splitting ratio of the 3-dB coupler and the photodiode responsivity mismatch. In addition, the filling of the circumference of the ellipse with points indicates that the DQPSK constellation rotates with average angular velocity equal to the angular intermediate frequency offset. The ellipse is left-handed if the intermediate frequency offset is positive and right-handed otherwise. The quadrature imbalance correction algorithm

1-4244-0927-6/07/$25.00/©2007 IEEE

calculates the parameters of the ellipse by least-squares fitting (red curve) [9] and then transforms the ellipse into a circle (Fig. 3(b)) using the orthogonalization procedure described in [10]. The implementation complexity and required execution time of the ellipse-fitting algorithm is adequate for off-line processing but might be prohibitive for real-time 10 GBd quadrature imbalance correction. As an alternative, a low implementation complexity, adaptive compensation of the quadrature imbalance could be used [11]. The non-zero intermediate frequency is estimated using two different feed-forward techniques, proposed by Tretter [5] and Kay [5]-[7], respectively, and removed. The phase noise is subsequently estimated using the method by [2], [3] and removed. Fig. 3(c) shows the recovered signal constellation. Fig. 4 shows the eye diagram of the in-phase component before (green color) and after the application of the DSP algorithm (red color). Fig. 3(c) and Fig. 4 indicate that the transmission is error-free.

In conclusion, we experimentally demonstrate that quadrature imbalance and intermediate frequency offset can have a significant impact on the performance of a coherent phase-diversity DQPSK receiver. We show that quadrature imbalance can be corrected using ellipse fitting and quadrature orthogonalization and that intermediate frequency offset can be estimated using low complexity, feed-forward, least-square-error based algorithms.

[1] J. M. Kahn and K.-P. Ho, *IEEE J. Sel. Top. Quantum Electron*., vol. 10, no. 2, pp. 259–272, Mar./Apr. 2004.
[2] R. Noé, *J. Lightw. Technol.*, vol. 23, pp. 802–808, Feb. 2005.
[3] K. Kikuchi, *IEEE J. Sel. Topics Quantum Electron*., vol.12, no.4, pp. 563–570, July-Aug. 2006.
[4] J. Crols and M. S. J. Steyaert, *IEEE J. Solid-State Circuits*, vol. 30, pp. 1483–1492, Dec. 1995..
[5] M. Morelli and U. Mengali, *European Trans. Telecom.*, vol. 2, pp. 103–116, Mar./Apr. 1998.
[6] U. Koc, A. Leven, Y. Chen, and N. Kaneda, in *Proc. Opt. Fiber Conf. (OFC)*, Anaheim, CA, 2006, Paper OThI1.
[7] A. Leven, N. Kaneda, U. V. Koc, and Y. K. Chen, *IEEE Photon. Technol. Lett*., vol. 19, no. 6, pp. 366–368, Mar. 2007.
[8] L. G. Kazovsky, L. Curtis, W. C. Young, and N. K. Cheung, *Appl. Opt.*, vol. 26, pp. 437–439, Feb. 1987.
[9] A. W. Fitzgibbon, M. Pilu, and R. B. Fisher, *IEEE Trans. on Pat. Analysis and Machine Intel*., vol. 21, no. 5, pp. 476–480, 1999.
[10] F. E. Churchill, G. W. Ogar, and B. J. Thompson, *IEEE Trans. on Aerosp. and Electr. Systems,* vol. AES-17, no.1, pp. 131–137, Jan.1981.
[11] E. Cetin, I. Kale, and R. C. S. Morling, *IEEE International Symposium on Circuits and Systems*, vol. IV, pp. 370–373, May 2001.

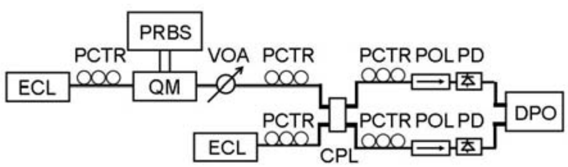

Fig. 1 Experimental setup (Abbreviations: ECL = external cavity laser, QM=quadrature modulator, PRBS = pseudo-random bit sequence generator, PCTR = polarization controller, VOA = variable optical attenuator, CPL = 3-dB coupler, POL = Fiber polarizer, PD = photodiode, DPO = digital phosphor oscilloscope).

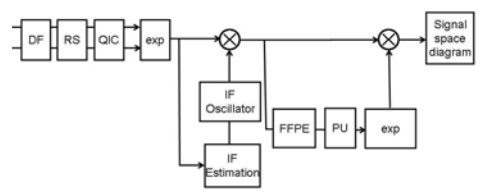

Fig. 2 Block diagram of the simulated receiver DSP ASIC (Abbreviations: DF = digital filter, RS = resampling, QIC = quadrature imbalance correction, IF = intermediate frequency, FFPE = Feed-forward phase estimation, PU = Phase unwrap).

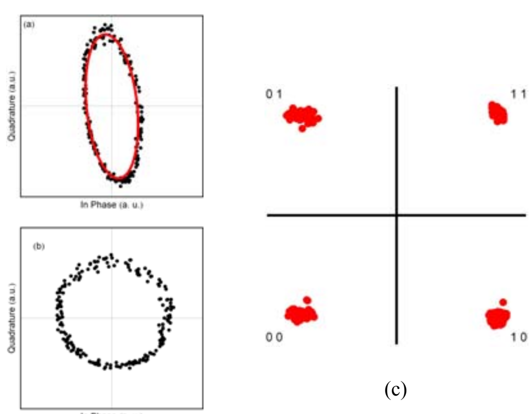

Fig. 3 (a) Parametric plot of the received quadrature components (points) and fit by an ellipse (red curve); (b) Same as before after correction of the quadrature imbalance; (c) Recovered signal constellation after subsequent intermediate frequency offset and phase noise cancellation.

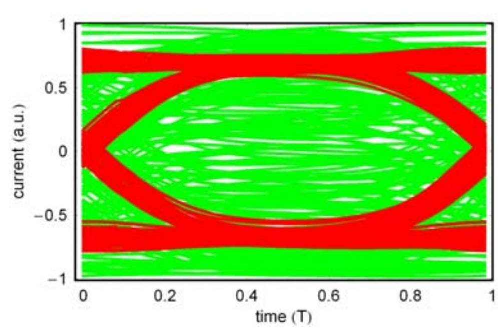

Fig. 4 Eye diagram for the in-phase component before (green color) and after correction of the quadrature imbalance, intermediate frequency offset and phase noise cancellation (red color)(Symbol: T = Symbol period).