Multiplier-Free Real-Time Phase Tracking for Coherent QPSK Receivers

Sebastian Hoffmann, Ralf Peveling, Timo Pfau, Olaf Adamczyk, Ralf Eickhoff, and Reinhold Noé

***Abstract*—This letter presents a hardware-efficient phase estimation algorithm that can replace the common complex estimators for a coherent quadrature phase-shift keying transmission system.**

***Index Terms*—Optical communication, phase estimation, quadrature phase-shift keying (QPSK), synchronous detection.**

I. Introduction

QUADRATURE phase-shift keying (QPSK) is a complex modulation format that has been the subject of several recent coherent detection real-time transmission experiments [1]–[4]. The major challenge of coherent QPSK transmission is the combination of general noise reduction combined with phase noise tracking, especeailly when standard distributed feedback (DFB) lasers are employed. Synchronous detection with digital feedforward phase estimators allows us to employ DFB lasers [1], [3], [5].

Fig. 1 shows the coherent receiver with the digital signal processing unit (DSPU). Sampled pairs of I and Q are represented as complex numbers and demultiplexed for parallel processing. If both frequency compensation and phase estimation were omitted, the receiver would be called asynchronous or differential. Differential encoding of the transmitted symbols enables such a data recovery based only on the received symbol and its predecessor. Frequency compensation is an alternative or a complement to the electronic local oscillator laser frequency control.

To remove the QPSK modulation in the phase estimator, it is common practice to raise the complex input signal or its normalized phasor to the power of 4. Afterwards, the additive noise is reduced by a low-pass filter, often a moving average over $2N+1$, where N is a small integer constant [5]–[9].

In a parallelized DSPU, it causes much effort to provide estimated phase values for each received symbol. In order to reduce this effort, block phase estimators generate only a single estimation value of M symbols processed in parallel [10], [11], but they are more sensitive to phase noise than averaging window estimators.

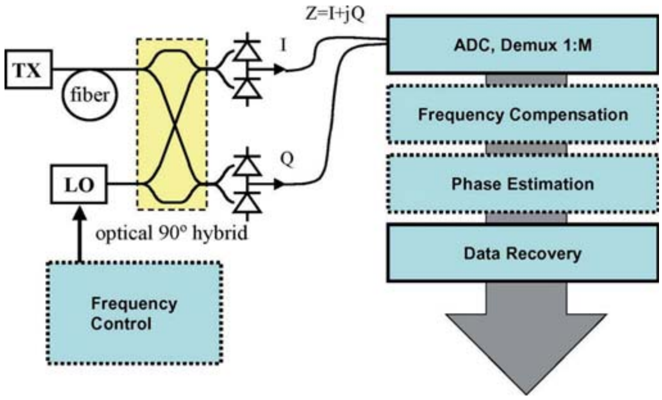

Fig. 1. Coherent QPSK receiver with DSPU. The DSPU processes M data streams in parallel.

We propose to employ an angle-based approach similar to the barycenter algorithm used for burst mode transmission in satelite communication [12]. This angle-based method avoids the complex calculations of usual phase estimators. Like the predecision-based method presented in [10], our approach is multiplier-free, but it does not require feedback and allows real-time tracking, not only block phase estimation. Moreover, the structure of the estimator allows us to use several intermediate results twice in the parallel processing which reduces the total effort. The low hardware effort was especially advantageous for the field programmable gate array implementation of this algorithm, used for the first real-time QPSK transmission [1] and also polarization multiplex and control [3].

II. Receiver With Complex Phase Estimator

The received symbols can be described as a sequence of complex numbers $Z(k)$ with time index k

$$Z(k) = c(k)e^{j\varphi(k)} + n(k). \tag{1}$$

$Z(k)$ consists of the QPSK symbol $c(k)$ multiplied by a time-variant phasor, and additive channel noise $n(k)$. The phasor is essentially a random factor representing the phase noise of both lasers. For the data recovery, only the argument of the received symbol is necessary [5], [7], [10]. For uniqueness, the operation $\bmod 2\pi$ is frequently added. The resulting positive angle is the

Manuscript received September 11, 2008; revised October 14, 2008. First published November 21, 2008; current version published January 14, 2009.

S. Hoffmann, R. Peveling, T. Pfau, and R. Noé are with the Institute of Electrical Engineering, University of Paderborn, 33098 Paderborn, Germany (e-mail: hoffmann@ont.uni-paderborn.de; peveling@hni.uni-paderborn.de; pfau@ont.uni-paderborn.de; noe@ont.uni-paderborn.de).

O. Adamczyk was with the Institute of Electrical Engineering, University of Paderborn, 33098 Paderborn, Germany, and is now with Nokia Siemens Networks, 81379 München, Germany (e-mail: olaf.adamczyk@nsn.com).

R. Eickhoff was with the Institute of Electrical Engineering, University of Paderborn, 33098 Paderborn, Germany, and is now with the Institute of Electrical Engineering, Technical Univeristy of Dresden, 01062 Dresden (e-mail: ralf.eickhoff@tu-dresden.de).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2009228

1041-1135/$25.00 © 2009 IEEE

sum of three different angles

$$\psi(k)=\arg(Z(k)) \bmod 2\pi=(\gamma(k)+\varphi(k)+\nu(k)) \bmod 2\pi. \tag{2}$$

The QPSK modulation contributes $\gamma(k) = \arg(c(k))$, while the additive channel noise contribution is $\nu(k)$. For phase estimation, it is necessary to remove the QPSK modulation. For an angle-based approach, a fold function can be employed which can simply be implemented by removing the first two bits of the argument in twos-complement representation [12]. We prefer the modulo operation to describe the effect of folding function in the following definition:

$$\vartheta(k) = \psi(k) \bmod \frac{\pi}{2}. \tag{3}$$

As desired, the positive angle $\vartheta(k)$ is independent from the QPSK modulation, a property that it shares with $Z^4(k)$ and to which it is related as follows:

$$\vartheta(k) = \frac{1}{4}\left(\arg(Z^4(k)) \bmod 2\pi\right). \tag{4}$$

Generating a modulation-free signal like $Z^4(k)$ is the task of the first stage of common complex phase estimators. An attractive alternative to $Z^4(k)$ is the normalized modulation-free signal $e^{j4\psi(k)} = e^{j4\vartheta(k)}$ [7], [9]. A further improvement of the complex phase estimation can be achieved by weighted averaging [8], [9]. The novel idea is to employ a set of modulation-free position angles $\vartheta(k-N)$, $\vartheta(k-N+1), \ldots, \vartheta(k+N)$ to obtain an estimated phase $\hat{\varphi}(k)$ immediately, i.e., without function tables and complex calculations. Angle-based averaging equivalent to the barycenter algorithm [12] is used to obtain a sequence of M estimated phase values in parallel. The proposed structure is very hardware-efficient and imitates weighted averaging by multiple usage of center values.

III. Angle-Based Phase Estimation

The sliding window phase estimation process for a single estimation value $\hat{\varphi}(k)$ can be described as a real-valued scalar function of a real-valued input vector with $2N+1$ components. To obtain a sequence of M estimated phase angles in parallel, an M-dimensional vector function $\hat{\Phi}$ of an input vector with $2N+M$ components is required

$$[\hat{\varphi}(k), \ldots, \hat{\varphi}(k+M-1)] = \widehat{\Phi}(\vartheta(k-N), \ldots, \vartheta(k+M+N-1)). \tag{5}$$

Fig. 2 shows the proposed angle-based parallelized tree structure for $N = 2$ and $M = 4$. The partial tree for the component $\hat{\varphi}(k+1)$ consists of the seven marked nodes. The nodes are basic cells that convert pairs of position angles α, β into average position angles μ. Basic cell functions $\mu(\alpha, \beta)$ are concatenated to form the phase estimator. Due to multiple usage of intermediate results, the vectorized function in Fig. 2 requires only 17 basic cells instead of $M \cdot 7 = 28$.

In order to imitate the behaviour of a Viterbi & Viterbi estimator with normalization [7], [9], the partial result from each basic cell has to be

$$\mu = \frac{1}{4}\left(\arg\left(e^{j4\alpha} + e^{j4\beta}\right) \bmod 2\pi\right). \tag{6}$$

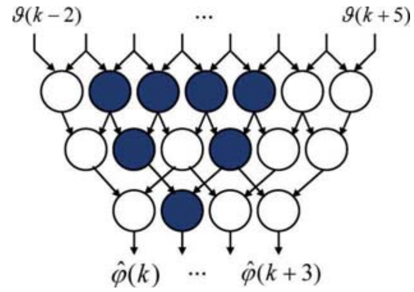

Fig. 2. Angle-based phase estimator structure.

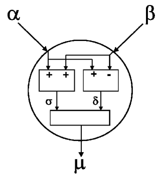

Fig. 3. Internal structure of the basic cell.

The complex sum in (6) can be rewritten as

$$e^{j4\alpha} + e^{j4\beta} = e^{j2\sigma} \cdot 2\cos(2\delta) \tag{7}$$

with the sum $\sigma = \alpha + \beta$ and the difference $\delta = \alpha - \beta$ of the input values. The argument of (7) depends on the exponent $j2\sigma$ and the sign of the cosine function because a negative sign of $\cos(2\delta)$ is equivalent to a rotation by π in the complex plane. Note that the cosine factor introduces a discontinuity of μ for $\delta \approx \pm\pi/4$. Taking the further operations of (6) into account, we obtain an alternative calculation formula for μ based on σ and δ only

$$\mu = \left(\frac{\sigma}{2} + \frac{\pi}{4}\left\lceil\frac{|\delta|}{\frac{\pi}{4}}\right\rceil\right) \bmod \frac{\pi}{2}. \tag{8}$$

Fig. 3 shows the internal structure of the basic cell. The two input values are added to and subtracted from each other in parallel, and the final result μ is generated from the auxiliary quantities σ and δ according to (8), all within one DSPU clock cycle. The quantity δ is a directed phase increment that could be used for frequency estimation as described in [9]. The basic cell performs an interpolation of the phase track on the shortest possible path. The estimation quality can be improved by selection, i.e., elimination of intermediate results from critical pairs α, β for which two possible paths have almost the same length. The acronym SMLPA (selective maximum likelihood phase approximation) refers to this feature.

IV. Simulation Results

The algorithm SMLPA was compared to a normalized block phase estimator with $M = 8$ and a normalized phase estimator with weighted averaging and $N = 5$ in a Monte-Carlo simulation. M is only important for the block phase estimator result, not for SMLPA or the weighted-normalized approach [9]. SMLPA with $N = 2$ as in Fig. 2 and a more complicated topology with $N = 4$ was employed. Asynchronous data recovery was also simulated . Bit-error ratio (BER) over optical signal-to-noise ratio (OSNR) curves were simulated with $4 \cdot 10^6$

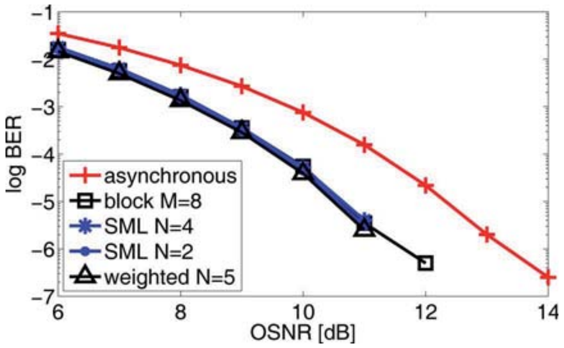

Fig. 4. BER/OSNR curves for different phase estimators for low phase noise.

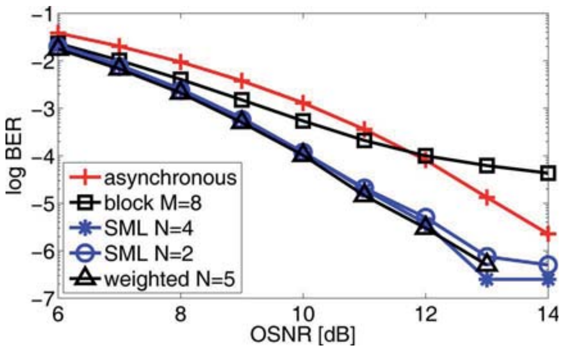

Fig. 5. BER/OSNR curves for different phase estimators for high phase noise.

random symbols for each BER value. DFB lasers with 1-MHz linewidth are assumed.

Fig. 4 shows the BER/OSNR results for a 28-GBaud system. With such a small relative linewidth, the block phase estimator performs almost as good as the other three phase estimators that track the phase drift.

Fig. 5 shows simulated BER/OSNR curves for the same phase estimators and a 10-GBaud system with DFB lasers that have 1-MHz linewidth and a residual frequency mismatch of 20 MHz. While the block phase estimator is not able to cope with high phase noise, both SMLPA versions have results similar to the weighted averaging method. They fulfill the high phase noise requirements of 10-GBaud transmission systems with coarsely controlled DFB lasers.

V. Summary

We have presented a novel and very hardware-efficient angle-based phase estimation algorithm that has proven to be a good replacement for the optimized moving average phase estimator. The presented simulation results for two different linewidth symbol rate ratios include asynchronous reception and block phase estimation.

References

[1] T. Pfau, S. Hoffmann, R. Peveling, S. Bhandare, S. Ibrahim, O. Adamczyk, M. Porrmann, R. Noé, and Y. Achiam, “First real-time data recovery for synchronous QPSK transmission with standard DFB lasers,” *IEEE Photon. Technol. Lett.*, vol. 18, no. 18, pp. 1907–1909, Sep. 15, 2006.

[2] A. Leven, N. Kaneda, A. Klein, U.-V. Koc, and Y.-K. Chen, “Real-time implementation of 4.4 Gbit/s QPSK intradyne receiver using field programmable gate array,” *Electron. Lett.*, vol. 42, no. 24, pp. 1421–1422, Nov. 23, 2006.

[3] T. Pfau, R. Peveling, F. Samson, J. Romoth, S. Hoffmann, S. Bhandare, S. Ibrahim, D. Sandel, O. Adamczyk, M. Porrmann, R. Noé, J. Hauden, N. Grossard, H. Porte, D. Schlieder, A. Koslovsky, Y. Benarush, and Y. Achiam, “Polarisation-multiplexed 2.8 Gbit/s synchronous QPSK transmission with real-time digital polarization tracking,” in *ECOC 2007*, vol. 3, pp. 263–264, Paper We 8.3.3.

[4] N. Kaneda, A. Leven, and Y.-K. Chen, “Block length effect on 5.0 Gbit/s real-time QPSK intradyne receivers with standard DFB lasers,” *Electron. Lett.*, vol. 43, no. 20, pp. 1106–1107, Sep. 27, 2007.

[5] R. Noé, “Phase noise tolerant synchronous QPSK/BPSK baseband-type intradyne receiver concept with feedforward carrier recovery,” *J. Lightw. Technol.*, vol. 23, no. 2, pp. 802–802, Feb. 2005.

[6] R. Noé, “PLL-free synchronous QPSK polarization multiplex/diversity receiver concept with digital I&Q baseband processing,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 4, pp. 887–889, Apr. 2005.

[7] A. J. Viterbi and A. N. Viterbi, “Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission,” *IEEE Trans. Inf. Theory*, vol. 29, no. 4, pp. 543–551, Jul. 1983.

[8] D. Van den Borne, C. R. S. Fludger, T. Duthel, T. Wuth, E. D. Schmidt, C. Schulien, E. Gottwald, G. D. Khoe, and H. De Waardt, “Carrier phase estimation for coherent equalization of 43-Gb/s POLMUX-NRZ-DQPSK transmission with 10.7-Gb/s NRZ neighbours,” in *ECOC 2007*, vol. 3, pp. 149–150, Paper We 7.2.3.

[9] S. Hoffmann, S. Bhandare, T. Pfau, O. Adamczyk, C. Wördehoff, R. Peveling, M. Porrmann, and R. Noé, “Frequency and phase estimation for coherent QPSK transmission with unlocked DFB lasers,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 18, pp. 1569–1571, Sep. 15, 2008.

[10] Z. Tao, L. Li, A. Isomura, T. Hoshida, and J. C. Rasmussen, “Multiplier-free phase recovery for optical coherent receivers,” in *OFC/NFOEC 2008*, San Diego, CA, Feb. 24–28, 2008, Paper OWT2.

[11] D.-S. Ly-Gagnon, S. Tsukamoto, K. Katoh, and K. Kikuchi, “Coherent detction of optical quadrature phase-shift keying signals with carrier phase estimation,” *J. Lightw. Technol.*, vol. 24, no. 1, pp. 12–21, Jan. 2006.

[12] M.-L. Boucheret, I. Mortensen, H. Favaro, and E. Belis, “A new algorithm for nonlinear estimation of PSK-modulated carrier phase,” in *ECSC-3*, Nov. 1993, pp. 155–159.