# Realtime Digital Polarization and Carrier Recovery in a Polarization-Multiplexed Optical QPSK Transmission

R. Noé, S. Hoffmann, T. Pfau, O. Adamczyk, V. Herath, R. Peveling, M. Porrmann

*University of Paderborn, EIM-E, Warburger Str. 100, 33098 Paderborn, Germany, http://ont.upb.de*

***Abstract*** **— This paper presents a phase estimation algorithm for a synchronous optical QPSK transmission system. The algorithm has been used in a digital signal processing unit for realtime carrier and data recovery. It has further been combined with polarization multiplex and electronic polarization control.**

***Index Terms*** **— Optical communication, quadrature phase shift keying, synchronous detection, polarization.**

## I. Introduction

Phase noise is a major impairment in coherent optical QPSK transmission with DFB lasers The contemporary approach to tackle this problem is to estimate the noisy carrier phase within a digital signal processing unit and use it for data recovery in a feedforward scheme [1]. A detailed study of feedforward carrier recovery was published in [2]. Compared to that non data-aided (NDA) soft decision phase estimator, a more general approach was presented by Viterbi and Viterbi [3].

Our approach combines the concept of normalization from [3] and weighted averaging which is similar to a Wiener filter suggested in [2] and [4]. First simulation results for this phase estimator were already presented in [5], but the algorithm was not explained in detail. We compare the various approaches [2,3,5] in a Monte Carlo simulation. Additionally we show how the linewidth tolerance of the carrier recovery is increased in a polarization-multiplexed receiver with a single carrier for both polarizations. The performance of the algorithm is verified in a realtime polarization-multiplexed QPSK transmission.

## II. Phase Estimation

The sampled received symbols of a coherent QPSK transmission system can be written as $Z(k) = c(k)\exp\{j(\omega_{IF} kT + \varphi(k))\} + n(k)$ where $Z(k)$ is a complex number consisting of the sent QPSK symbol $c(k)$ multiplied by a time-variant phasor, and additional noise $n(k)$. The argument of the phasor can be separated into an intermediate frequency (IF) part $\omega_{IF} kT$, which we assume to be 0, and a random part $\varphi(k)$ representing the phase noise.

A Viterbi phase estimator [3] transforms the complex symbol into polar coordinates, $Z(k) = |Z(k)|\exp\{j\psi(k)\}$ with magnitude $|Z(k)|$ and phase $\psi(k)$. Afterwards, a new complex modulation-free signal $Y(k)$ is generated,

$$Y(k) = |Z(k)|^p \exp\{j4\psi(k)\} \quad p \in \{0,2,4\}. \tag{1}$$

Choosing $p = 4$ is equivalent to the common complex approach $Y(k) = Z^4(k)$ [1,2]. Choosing $p = 0$ yields a normalized input signal $Y(k) = e^{j4\psi(k)}$ which is easy to calculate and contains reduced noise and distortions. The continuous phase estimation uses $2N+1$ values of the complex signal $Y(k)$ to generate a moving average. A high value of $N$ results in a smooth estimated phase but the low bandwidth of this filter limits its tracking capability. Small $N$ lead to higher sensitivity against noise. Weighted averaging

$$\langle Y(k)\rangle = \frac{1}{2N+1}\sum_{n=k-N}^{k+n} g_{n-k} Y(n) \tag{2}$$

with symmetrically decaying coefficients $g_0 \ge g_{\pm1} \ge g_{\pm2} \ge \ldots \ge g_{\pm N} > 0$ outperforms simple unweighted averaging [5]. Finally, the averaged signal $\langle Y(k)\rangle$ has to be converted into an estimated phase where the fourfold ambiguity of $\sqrt[4]{\langle Y(k)\rangle}$ has to be resolved, e.g. by the assignment $\hat{\varphi}(k) := 1/4 \cdot \arg\langle Y(k)\rangle \bmod \pi/2$. An estimated phase that is always chosen from a $\pi/2$-wide fixed interval is called a wrapped phase. The wrapped estimated phase has either to be unwrapped [4], or jump numbers have to be generated for the data recovery [1].

If the described phase estimation algorithm is to be employed in a polarization multiplex system, there are two possibilities to use the argument pair $\psi_1(k), \psi_2(k)$ of the received and compensated complex symbol vector [1]. One of them is to generate estimated phases $\hat{\varphi}_1(k), \hat{\varphi}_2(k)$ for both channels separately as proposed in [2]. The other is to use a common estimated phase for both channels [1]. Because the intermediate frequency and phase noise random walk of both channels is caused by the same lasers, it is advantageous to choose the second possibility and to use all available data for a single phase estimation, by modifying (1) for $p = 0$ into

$$Y(k) = \exp\{j4\psi_1(k)\} + \exp\{j4\psi_2(k)\}. \tag{3}$$

The sequence $Y(k)$ is again used for weighted averaging according to (2). Note that $Y(k)$ is not normalized in the literal sense anymore; but the result of (2) is a weighted average of $2(2N+1)$ normalized values. The summation in (3) simplifies computation because the sum $Y(k)$ has to be multiplied with several weighting coefficients afterwards.

In a polarization diversity receiver, the detected electronic Jones vector must be multiplied by the electronic inverse of the fiber Jones matrix. This process is described in [6].

## III. Simulation & measurement results

Fig. 1 shows simulated BER curves for three different phase estimation algorithms (Viterbi [3] with $p$=4, $p$=0 and $p$=0 combined with weighting) with $N$=5. They are compared to a simple differential ($N$=0, also called asynchronous) receiver in a Monte-Carlo simulation. BER/SNR curves with $10^7$ symbols for each BER value were generated for a linewidth / symbol rate ratio of 0.001. This corresponds to a sum laser linewidth of 10 MHz in a 10 Gbaud system. The algorithm with $p$=0 and weighted coefficients achieves a 0.1 dB better sensitivity than the algorithm with equal weights. Compared to the Viterbi filter with $p$=4, a 0.3 dB sensitivity improvement is achieved.

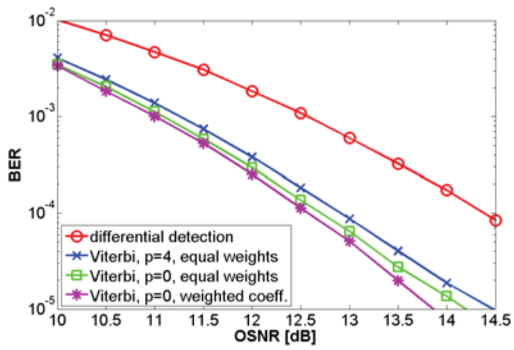


*Fig. 1 Simulated BER vs. OSNR for carrier recovery approaches.*

In another simulation we compare the phase noise tolerance between two polarization-multiplexed receivers. The first one uses a separate carrier recovery for each polarization, the second one used a combined carrier recovery for both polarizations as described in II. Fig. 2 shows the tolerable sum linewidth / symbol rate ratio vs. different numbers of samples used for the carrier recovery. It is assumed that a 0.5 dB penalty induced by laser phase noise is acceptable. The combined carrier recovery tolerates more than twice as high laser linewidths than the two separate carrier recoveries.

Polarization control [6] and the carrier recovery algorithm with $p$=0 and weighted averaging have been implemented in slightly modified form in an FPGA-based realtime polarization-multiplexed coherent receiver with combined carrier recovery for both polarizations. They have been tested at a data rate of 2.8 Gb/s (Fig. 3). The achieved BER floor is $1.2\cdot10^{-7}$. Considering the specified sum linewidth of 2 MHz of the utilized lasers this is even below the corresponding simulated BER floor of $3.8\cdot10^{-7}$. This can be explained by the fact that lasers usually have a slightly smaller linewidth than specified in the data sheet.

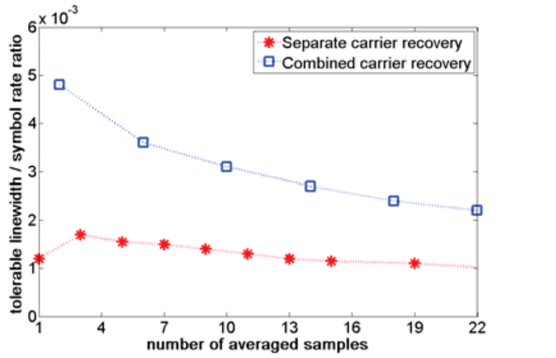


*Fig. 2 Laser linewidth tolerance for different numbers of input samples into the carrier recovery.*

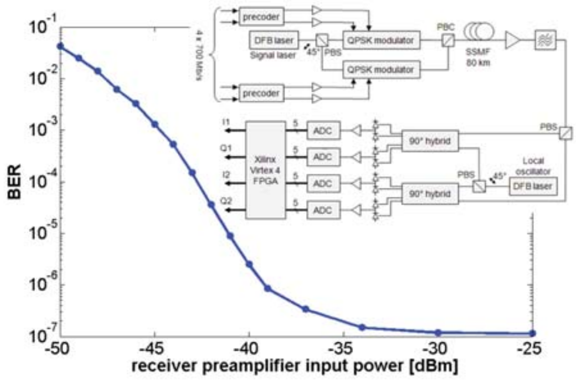


*Fig. 3 Carrier recovery performance in a 2.8 Gb/s realtime coherent polarization-multiplexed QPSK transmission experiment.*

## IV. Conclusion

We have presented a hardware-efficient carrier recovery concept, which has been implemented in a realtime coherent receiver. It outperforms existing concepts by at least 0.1 dB. Additionally it was shown that a combined carrier recovery for both polarizations in a polarization-multiplexed receiver has a more than twice as high tolerance against laser phase noise than two separate carrier recoveries.

## References

[1] R. Noé, "Phase Noise Tolerant Synchronous QPSK/BPSK Baseband-Type Intradyne Receiver Concept with Feedforward Carrier Recovery", IEEE JLT, Vol. 23, 2005, pp. 802-808.

[2] E. Ip et al., Feedforward Carrier Recovery for Coherent Optical Communications, IEEE JLT, Vol. 25, 2007, pp. 2675-2692

[3] A. Viterbi et al., Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission. IEEE Trans. on Information Theory, vol. 29, No 4, pp. 543-551, 1983

[4] M. G. Taylor, Accurate digital phase estimation process for coherent detection using a parallel digital processor, Proc. ECOC Sept. 2005, vol. 2, pp. 263-264

[5] S.Hoffmann et al., "Hardware-Efficient and Phase Noise Tolerant Digital Synchronous QPSK Receiver Concept", OAA/COTA2006, CThC6, Whistler, Canada, June 28-30, 2006

[6] R. Noé, PLL-Free Synchronous QPSK Polarization Multiplex/Diversity Receiver Concept with Digital I&Q Baseband Processing, IEEE Photon. Technol. Lett., Vol. 17, 2005, pp. 887-889