# Analysis of Carrier Phase Extraction Methods in 112-Gbit/s NRZ-PDM-QPSK Coherent Transmission System

**Tianhua Xu[1,2,3], Gunnar Jacobsen[2], Sergei Popov[1], Jie Li[2], Sergey Sergeyev[4], Yimo Zhang[3]**

*1. Royal Institute of Technology, Stockholm, SE-16440, Sweden,*
*2. Acreo AB, Electrum 236, SE-16440, Kista, Sweden,*
*3. Tianjin University, Tianjin, 300072, China,*
*4. Aston University, Birmingham, B47ET, UK*
*Author e-mail address: tianhua@kth.se*

**Abstract:** We present a comparative analysis on three carrier phase extraction approaches, including a one-tap normalized least mean square method, a block-average method, and a Viterbi-Viterbi method, in coherent transmission system considering equalization enhanced phase noise.

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## 1. Introduction

High bit rate optical communication systems put strong requirements of their tolerance to linear and nonlinear channel impairments. Coherent optical receivers using digital signal processing (DSP) techniques can mitigate the system impairments, such as chromatic dispersion (CD), polarization mode dispersion (PMD) and phase noise (PN) in the electrical domain [1,2]. Several feed-forward and feed-back carrier recovery algorithms have been validated as effective methods for carrier phase estimation (CPE) [3-5]. However, the analysis of the phase fluctuation is usually performed without considering the influence of large chromatic dispersion. W. Shieh and A. P. T. Lau et al. have proposed the theory of equalization enhanced phase noise (EEPN) in digital coherent communication system [6,7], and C. Xie has also reported the similar phenomena [8].

In this paper, we investigate the behavior of different carrier phase extraction algorithms in 112-Gbit/s non-return-to-zero polarization division multiplexed quadrature phase shift keying (NRZ-PDM-QPSK) coherent optical transmission system. The performance of three carrier phase estimation algorithms, including a normalized least mean square (NLMS) method, a block-average (BA) method and a Viterbi-Viterbi (VV) method are comparatively analyzed considering the impacts of EEPN [3-5].

## 2. Principle of equalization enhanced phase noise

In the coherent optical system using post implementation of digital CD equalization and carrier phase estimation, the transmitter (TX) laser phase noise passes through both the transmission fiber and the digital CD equalization module, and so the net dispersion experienced by the transmitter PN is close to zero. However, the local oscillator (LO) phase noise goes only through the digital CD equalization module, which is heavily dispersed in a transmission system without dispersion compensation fibers (DCFs). Therefore, the LO phase noise will significantly influence the performance of the high speed coherent system with only digital CD compensation. Theoretical analysis demonstrates that the EEPN scales linearly with the accumulated CD and the linewidth of the LO laser [6,7].

## 3. Principle of carrier phase estimation algorithms

### 3.1 Normalized LMS filter

The one-tap NLMS filter can be employed effectively for carrier phase estimation [3], of which the tap weight is expressed as

$$w(n+1) = w(n) + \mu \cdot x^*(n)e(n) \big/ \left|x(n)\right|^2 \qquad (1)$$

$$e(n) = d(n) - w(n) \cdot x(n) \qquad (2)$$

where $w(n)$ is the complex tap weight, $x(n)$ is the complex magnitude of the input signal, $n$ represents the number of the symbol sequence, $d(n)$ is the desired symbol, $e(n)$ is the estimation error between the output signals and the desired symbols, and $\mu$ is the step size parameter.

### 3.2 Block-average phase extraction

The block-average method computes the 4-th power of the symbols in each process unit to cancel the phase modulation in QPSK system, and the calculated phases are summed and averaged over the entire block (process unit). Then the phase is divided by 4, and the result leads to the phase estimation for the entire block [4]. The estimated phase in each process unit using the BA method can be expressed as

$$\hat{\Phi}_{BA}(n)=\frac{1}{4}\arg\left\{\sum_{k=1+(m-1)\cdot N_b}^{m\cdot N_b} x^4(k)\right\} \quad (3)$$

$$m=\lceil n/N_b \rceil \quad (4)$$

where $\lceil x \rceil$ represents the nearest integer lager than $x$.

3.3 Viterbi-Viterbi phase extraction

The Viterbi-Viterbi method also processes the symbols in each process unit into the 4-th power to cancel the phase modulation in QPSK system. Meanwhile, the calculated phases are also summed and averaged over the entire block. However, the difference with regard to the BA method is in the final step, where the extracted phase in the VV method is only concerned as the phase estimation for the central symbol in each block [5]. The estimated phase using the Viterbi-Viterbi method can be expressed as

$$\hat{\Phi}_{VV}(n)=\frac{1}{4}\arg\left\{\sum_{k=-(N_v-1)/2}^{(N_v-1)/2} x^4(n+k)\right\},\ N_v=1,3,5,7\ldots \quad (5)$$

We can find that compared to the BA method, the Viterbi-Viterbi method will have a smaller phase estimate error, but it requires more computational complexity to update the process unit for each symbol phase estimation.

## 4. High speed PDM-QPSK coherent optical transmission system

The setup of the 112-Gbit/s NRZ-PDM-QPSK coherent optical transmission system implemented in the VPI simulation platform is illustrated in Fig. 1 [9]. The data sequence output from the four 28-Gbit/s pseudo random bit sequence (PRBS) generators are modulated into two orthogonally polarized NRZ-QPSK optical signals by two Mach-Zehnder modulators (MZM). The orthogonally polarized signals are fed into one fiber channel by a polarization beam combiner (PBC) to form the 112-Gbit/s NRZ-PDM-QPSK optical signal. Using a local oscillator in the coherent receiver, the received optical signals are mixed with the LO laser to be transformed into four electrical signals by the photodiodes (PD). These signals are digitalized by the 8-bit analog-to-digital convertors (ADCs) at twice the symbol rate. The transmission fibers have the CD coefficient equal to 16 ps/nm/km, and the central wavelengths of the TX laser and the LO laser are both 1553.6 nm. The CD compensation is performed by using a frequency domain blind look-up (BLU) filter [2]. For simplicity, the influences of fiber attenuation, polarization mode dispersion and nonlinear effects are neglected in this study.

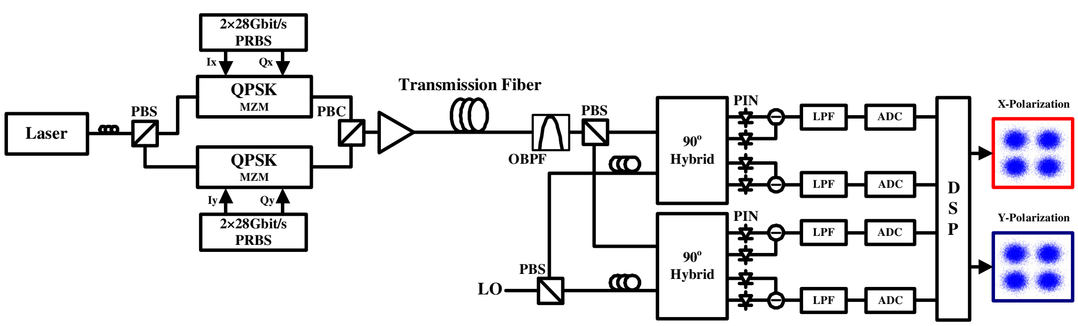

Fig. 1. Block diagram of 112-Gbit/s NRZ-PDM-QPSK coherent optical transmission system

## 5. Simulation results and discussion

As shown in Fig. 2, we have investigated the bit-error-rate (BER) floor using the three carrier phase extraction methods in the 112-Gbit/s NRZ-PDM-QPSK coherent optical transmission system, where the EEPN is considered. In this simulation work, the optical fiber length is 2000 km, and the linewidths of the TX and the LO lasers are both 5 MHz. The numerical results are obtained with different block size in the BA and the VV carrier phase extraction methods, and a fixed optimum step size in the NLMS method. It is found that the block-average method behaves a little better than the NLMS method when the block size is less than 11, and the Viterbi-Viterbi method also works slightly better than the NLMS method when the block size is less than 21. On the other hand, the Viterbi-Viterbi method does not show a considerable improvement compared to the block-average method, even if it sacrifices more computational complexity.

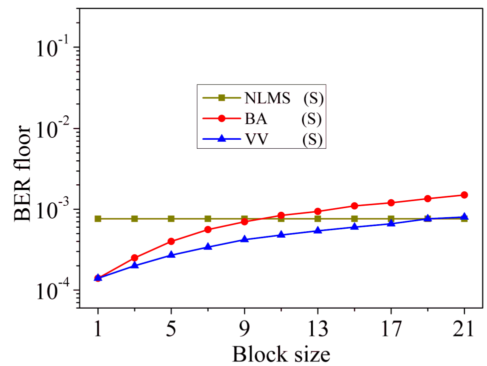


Fig. 2. The coherent detection results using three carrier phase estimation methods with different block size.

The weak dependence on the block size in the BA and the VV algorithms implies that the additive noise in the transmission channel of the practical coherent systems can be accommodated quite well, since this requires a large block size (up to 20) to mitigate the additive Gaussian noise. Meanwhile, the NLMS method can also show a good performance with the additive noise in the transmission channel, if the step size is optimized [3,10].

It is also worth noting that the NLMS algorithm can be employed for the high level modulation format such as the *n*-PSK and the *n*-QAM transmission systems, while the block-average and the Viterbi-Viterbi methods can not be easily used for the classical *n*-QAM coherent systems except the circle *n*-QAM system.

## 6. Conclusions

In this paper, the performance of different carrier phase extraction methods considering the equalization enhanced phase noise is investigated in the 112-Gbit/s NRZ-PDM-QPSK coherent optical transmission system. In the numerical simulation, the NLMS method can still show an acceptable behavior compared to the other two approaches. Moreover, the Viterbi-Viterbi method can only show a slight improvement compared to the block-average method, even if it sacrifices more computational complexity.

## 7. References

[1] S. J. Savory, "Digital filters for coherent optical receivers," OE **16**, 804-817 (2008).

[2] M. Kuschnerov, F. N. Hauske, K. Piyawanno, B. Spinnler, A. Napoli and B. Lankl, "Adaptive chromatic dispersion equalization for non-dispersion managed coherent systems," in OFC 2009 (San Diego, California, 2009), paper OMT1.

[3] Y. Mori, C. Zhang, K. Igarashi, K. Katoh and K. Kikuchi, "Unrepeated 200-km transmission of 40-Gbit/s 16-QAM signals using digital coherent receiver," OE **17**, 1435-1441 (2009).

[4] D. S. Ly-Gagnon, S. Tsukamoto, K. Katoh, and K. Kikuchi, "Coherent detection of optical quadrature phase-shift keying signals with carrier phase estimation," JLT **24**, 12-21 (2006).

[5] A. Viterbi, "Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission," IEEE Trans. Inf. Theory **29**, 543-551 (1983).

[6] W. Shieh and K. P. Ho, "Equalization-enhanced phase noise for coherent detection systems using electronic digital signal processing," OE **16**, 15718-15727 (2008).

[7] A. P. T. Lau, W. Shieh and K. P. Ho, "Equalization-enhanced phase noise for 100Gb/s transmission with coherent detection," in OECC 2009 (OptoElectronics and Communications Conference, Hong Kong, 2009), paper FQ3.

[8] C. Xie, "Local oscillator phase noise induced penalties in optical coherent detection systems using electronic chromatic dispersion compensation," in OFC 2009 (San Diego, California, 2009), paper OMT4.

[9] www.vpiphotonics.com

[10] T. Xu, G. Jacobsen, S. Popov, J. Li, A. T. Friberg and Y. Zhang, "Analytical estimation of phase noise influence in coherent transmission system with digital dispersion equalization," OE **19**, 7756-7768 (2011).