Dual stage carrier phase estimation for 16-QAM systems based on a modified QPSK-partitioning

Dual Stage Carrier Phase Estimation for 16-QAM Systems Based on a Modified QPSK-Partitioning Algorithm

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ABSTRACT
Coherent optical communications based on higher order modulation formats are severely affected by the phase noise of transmitter and receiver lasers. In this work, a novel yet simple scheme is presented for carrier phase estimation (CPE) of 16-ary Quadrature Amplitude Modulation (16- QAM) formats, based on a modified QPSK-partitioning algorithm. The proposed algorithm can tolerate a linewidth times symbol duration product ($\Delta\nu \cdot T_s$) of the order of 10^{-4}, with 1 dB penalty at a bit error rate (BER) of 10^{-3}. Tolerance can be further improved by introducing a maximum likelihood estimation (MLE) stage ($\Delta\nu \cdot T_s \approx 1.432 \times 10^{-4}$). Comparison of the scheme with other proposed algorithms is shown. The obtained results indicate that the presented approach can be used with the commercially available state of the art lasers for 16-ary Quadrature Amplitude Modulation (16- QAM) transmission at 100 Gbps.
Keywords: Carrier phase recovery, Quadrature amplitude modulation (QAM), Viterbi & Viterbi algorithm, QPSK-partitioning, Maximum Likelihood Estimation (MLE).

1. INTRODUCTION

Phase noise is considered to be one of the main impairments in coherent optical communication systems when high-order modulation formats are employed. An electrical or optical phase locked loop (PLL) is traditionally considered for demodulating coherent optical signals. It provides synchronization between the transmitter laser and local oscillator's (LO) phase and frequency. However PLL's are subjected to propagation delays within the loop and ultimately results in loop instability [1]. Also for coherent detection, laser linewidth requirements are very strict for PLL's [1].

Owing to the advances in very large scale integration (VLSI) technology, digital signal processing (DSP) algorithms now can be used for the compensation of channel impairments. Moreover, digital coherent receivers can provide new methods for carrier synchronization. Due to this fact, PLL's can be avoided, since DSP can be used to track the mismatch of frequency between the LO and transmitter laser. A feed forward architecture, such as the one shown in Fig. 1, can be used for the compensation of frequency mismatch between the LO and transmitter laser, for various Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) formats. Experiments have shown that the carrier recovery schemes using the feed forward architecture are more immune to phase noise than PLL's [2].

16-ary Quadrature Amplitude Modulation (16-QAM) is considered to be among the most promising formats for the future 100 Gbps systems. At 14 Gbaud, using 16-QAM wavelength division multiplexing (WDM), spectral efficiency of 6.2 b/s/Hz has been experimentally demonstrated [5]. Hence 16-QAM can be considered as a promising key technology for increasing the spectral efficiency of optical transmission and to overcome the limitations of existing fiber infrastructure. For 16-QAM systems, various PE Algorithms have been proposed and established [3]−[8]. In this paper, we propose a modified version of the Viterbi & Viterbi algorithm based on QPSK-partitioning, which allows the performance to be further improved with a negligible increase in complexity.

2. PE ALGORITHM OVERVIEW

The algorithms based on M-th Power schemes are comparatively simple and have much relaxed laser linewidth requirements than the closed loop schemes [9]. However, the M-th Power algorithm is commonly used for QPSK or mPSK formats. It cannot be used for 16-QAM in its original version, since it is not possible to reduce the 16-QAM constellations to a single phase vector through a $(.)^M$ operation. The algorithm proposed in [4] estimates the phase error by considering only the subgroup symbols with modulation angles equal to $\pi/4 + m \cdot \pi/2$ (m=0…3). Since only a subgroup of the symbols is considered, a large number of symbols are needed to provide a satisfactory phase estimate. The performance of M-th power scheme is adapted to multi-modulus modulation formats in [6] and [10] by using QPSK partitioning. In [6], an additional mechanism was needed to avoid the propagation of phase error, if a symbol is incorrectly sorted in a sub-class. In [10], the proposed scheme complexity has increased by four real adders and eight real multipliers, for each particular sub-group symbol.

In this paper we propose a novel yet simple approach that considers all the symbols for the phase estimate. The flow chart of the proposed scheme is shown in Fig. 2. Performance of the scheme for different linewidth times symbol duration products ($\Delta\nu \cdot T_s$) is also observed, finding that, for a 1-dB penalty at a bit error rate (BER) of

10^{-3}, the proposed scheme can tolerate $\Delta\nu \cdot T_s$ approximately equal to 10^{-4}. Hence at 100 Gbps, the proposed scheme can be used with the commercially available state of the art lasers for 16-QAM transmission.

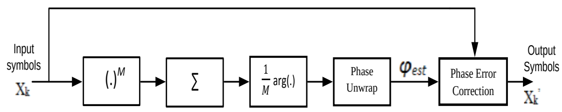

Figure 1. M-th Power, Viterbi & Viterbi, Feed Forward Architecture

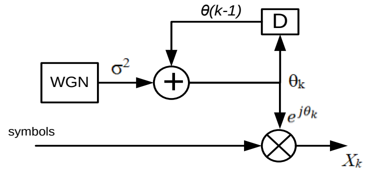

Figure 3. Phase Noise Model

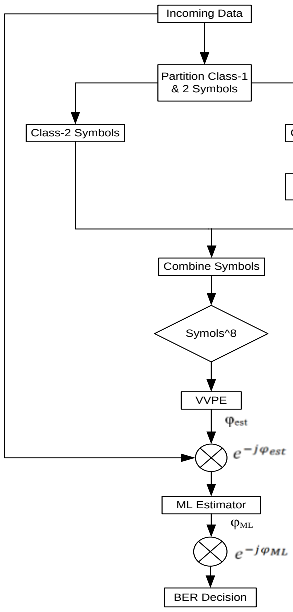

Figure 2. Flow Chart of Proposed Scheme

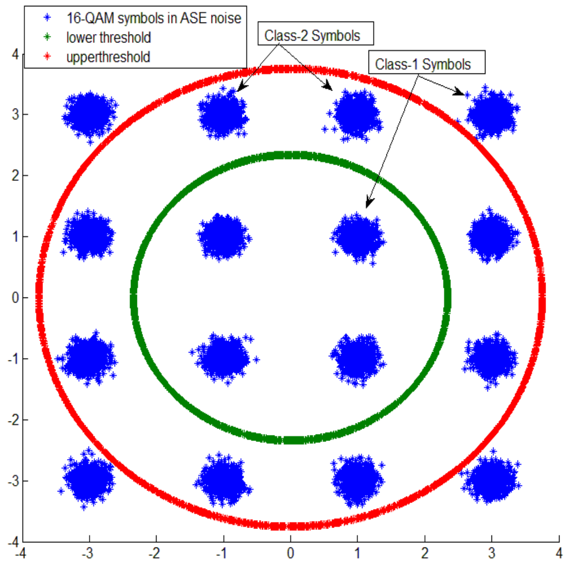

Figure 4. 16-QAM constellation indicating both Class 1&2 symbols along with the ASE noise

3. DESCRIPTION OF CPE TECHNIQUE

Fig. 4 shows the constellation plot of a 16-QAM system. The subgroup symbols inside the green and outside the red circles are called Class-1 symbols, whereas the subgroup symbols in-between these two circles are called Class-2 symbols. Both the circles indicate the thresholds to separate the symbols of different amplitudes. One possible approach consists in performing phase error estimation and compensation using only Class-1 symbols. The complex samples are raised to the 4-th power to remove the phase modulation. To increase the accuracy of the estimate, a moving average with a uniform window of length N_1 symbols is performed. By finding the angle of the complex sum vector, a phase error estimate is obtained for this block. For the sake of phase error estimation, the complex samples have to be normalized before they can be summed up:

$$\varphi_{est,class1} = \frac{1}{4} \arg \sum_{k=1}^{N_1} \frac{X_k^4}{\left|X_k^4\right|} \tag{1}$$

The performance of this estimator can be improved by adding an (optional) maximum-likelihood estimation (MLE) stage, as shown in [11]. The expression of the ML estimator is: $\varphi_{ML} = \tan^{-1}(img(z)/real(z))$, with $z = \frac{1}{4} arg \sum_{k=1}^{N_2} x_k \cdot y_k^*$, where y_k is the decision of x_k and N_2 is the block length for the MLE stage.

Our proposed approach includes in the phase error estimate also Class-2 symbols. As compared to Class-1 symbols, Class-2 symbols do-not lie at an angle of m·π/4 (m=1, 3, 5, 7). In-fact they lie at an angle of ± 4° from m·π/8 (m=1, 3, 5…….15). By raising them to the power of 8, they can approximately be reduced to single phase vectors. Hence it is possible to get a phase error estimate from Class-2 symbols, simply by raising them to the power of eight, instead of four and then applying the conventional VVPE algorithm.

$$\varphi_{est,class2} = \frac{1}{8} \arg \sum_{k=1}^{N_1} \frac{X_k^8}{\left|X_k^8\right|} \tag{2}$$

Note that, if the averaging window is sufficiently long, the ±4° error is averaged out and the estimation of phase noise is only marginally affected by these errors.

The estimation obtained by using only Class-2 symbols, especially at high phase noise, is close enough but not as good as Class-1 symbols. A better phase error estimate can be obtained by using both Class-1 and Class-2 symbols. In order to do this, Class-1 symbols are rotated by π/8 to approximately align them to Class-2 symbols, as shown in Fig. 7. Then all the symbols are raised to the power of eight and the same conventional VVPE algorithm is applied for the phase error estimate:

$$\varphi_{est,class1\&2} = \frac{1}{8}\arg\sum_{k=1}^{N_1}\frac{X_k^8}{\left|X_k^8\right|} \tag{3}$$

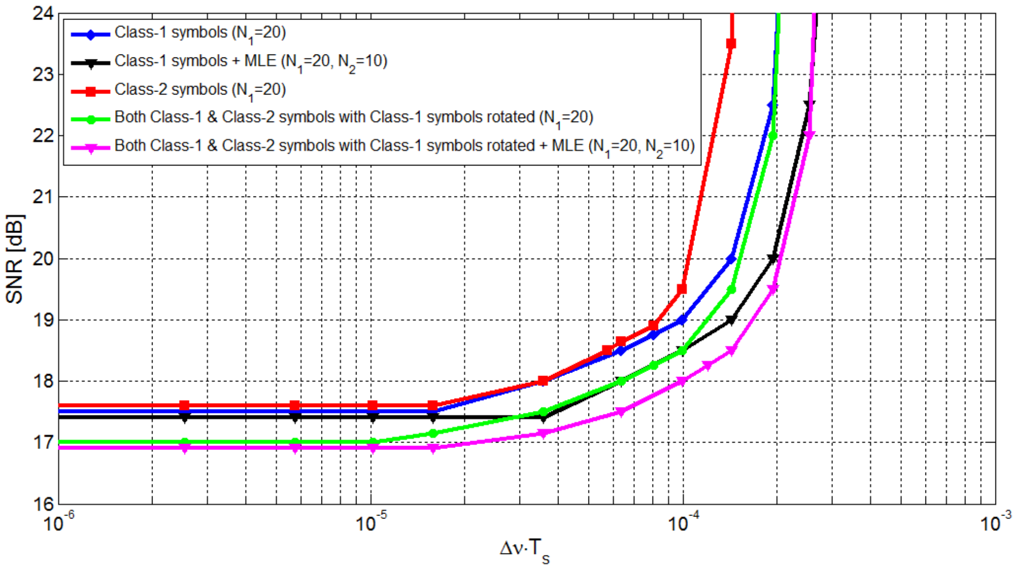

Figure 5. SNR vs. Linewidth times symbol duration ($\Delta\nu \cdot T_s$) for phase error estimate obtained by using Class-1, Class-2 & both Class-1&2 symbols

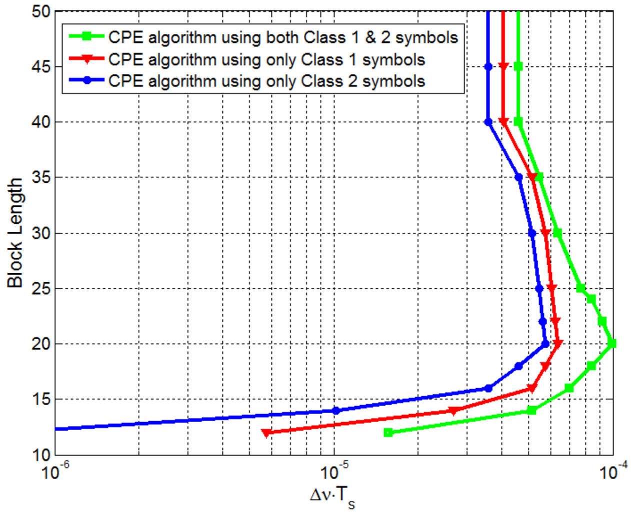

Figure 6. Block length vs. Linewidth times symbol duration ($\Delta\nu \cdot T_s$)

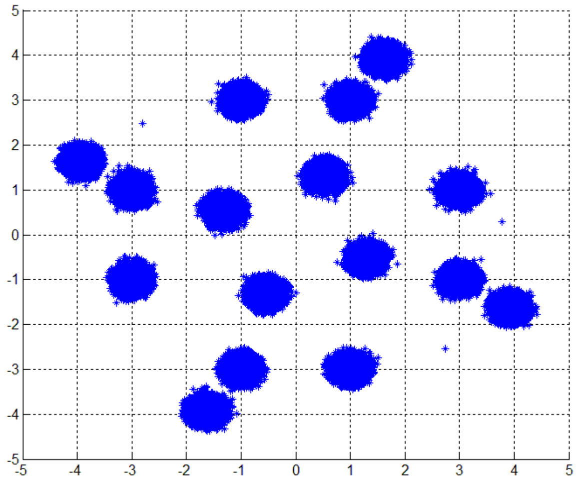

Figure 7. 16-QAM constellation plot with class-1 symbols rotated by π/8 and approximately aligned with the Class-2 symbols

4. SIMULATION RESULTS AND ANALYSIS

In this section we compare by simulation the performance of the various CPE algorithms described in Section 3. The signal samples at the output of the digital coherent receiver can be written as: $y_k = x_k e^{j\theta_k} + \eta_k$, where x_k is the data symbol that belongs to the set {±1 ± j, ±3 ± j, ±1 ± 3j, ±3 ± 3j} and η_k is the additive white Gaussian noise (AWGN), which models for instance the ASE noise introduced by optical amplifiers. θ_k is the laser phase noise and is modelled as a Wiener process [12] (see Fig. 3): $\theta_k = \sum_{i=-\infty}^{k} \nu_i$, where ν_i's are independent and identically distributed Gaussian random variables with zero mean and variance $\sigma_f^2 = 2\pi\Delta\nu T_s$, $\Delta\nu$ is the combined laser linewidth of transmitter laser and LO and T_s is the symbol period.

Fig. 5 shows the performance comparison between the QPSK partitioning algorithms described in the previous section, considering Class-1, Class-2 or both Class-1 and Class-2 symbols, in terms of SNR required to obtain a BER equal to 10^{-3} as a function of the product $\Delta\nu \cdot T_s$. The maximum tolerable value of $\Delta\nu \cdot T_s$ to keep the SNR penalty below 1 dB was found to be $6.4 \cdot 10^{-5}$, $5.7 \cdot 10^{-5}$ and $9.9 \cdot 10^{-5}$, for Class-1 symbols, Class-2 symbols and both Class-1 & Class-2 symbols respectively. After MLE, the tolerance is increased to $\Delta\nu \cdot T_s = 9.9 \cdot 10^{-5}$ and $1.4 \cdot 10^{-4}$ for the methods using Class-1 symbols only and both Class-1 & Class-2 symbols, respectively.

Fig. 6 shows the values block lengths (i.e. the length of the Viterbi&Viterbi averaging window) corresponding to a sensitivity penalty of 1dB: for each linewidth, all values of block length between the lower and upper part of the curve allow to keep the penalty lower than 1 dB. The value which maximizes the linewidth tolerance in all cases is around 20 symbols ($N_1=20$). Performing a similar analysis, the optimum block length for MLE stages was found to be 10 symbols ($N_2=10$).

The improvement in linewidth tolerance of the algorithm employing both Class-1 and Class-2 symbols (w/o MLE) with respect to [4] is due to the fact that all the symbols are considered for the phase error estimate. In comparison to the method used in [6], no additional mechanism is required to avoid the propagation of phase error, in case of a situation in which a symbol is incorrectly sorted in a sub-class. Finally, the proposed algorithm yields similar linewidth tolerance as the one described in [10], with lower additional complexity with respect to a QPSK partitioning algorithm employing Calss-1 symbols only.

5. CONCLUSION

A novel feed forward carrier phase estimation algorithm for a 16-QAM system has been presented. Different stages involving partition, selection and rotation of symbols have also been discussed. For an OSNR penalty of 1 dB at BER=10^{-3}, the proposed algorithm can tolerate a linewidth times symbol rate product around 10^{-4}, making it suitable for the use in 100Gbps 16-QAM optical systems with commercially available state of the art lasers.

REFERENCES

[1] E. Ip, *et al.*: Feedforward carrier recovery for coherent optical communications, *J. Lightwave Technol.*, vol. 25, pp. 2675–2692, Sep. 2007.

[2] K. Kikuchi: Coherent detection of phase-shift keying signals using digital carrier-phase estimation, *in OFC/NFOEC*, Mar 2006, paper OTuI4.

[3] I. Fatadin, *et al.*: Blind equalization and carrier phase recovery in a 16-QAM optical coherent system, *J. Lightwave Technol.*, vol. 27, pp. 3042 –3049, Aug. 2009.

[4] M. Seimetz: Laser linewidth limitations for optical system with high-order modulation employing feed forward digital carrier phase estimation, *in OFC/NFOEC 2008*, Feb 2008.

[5] P. Winzer, et al.: Spectrally efficient long-haul optical networking using 112-gb/s polarization-multiplexed 16-QAM, *J. Lightwave Technol.*, vol. 28, pp. 547–556, Feb. 2010.

[6] H. Louchet, K. Kuzmin, A. Richter: Improved DSP algorithms for coherent 16-QAM transmission, *in ECOC 2008*, Sep. 2008, paper Tu.1.E.6.

[7] Zhang, P. Kam, C. Yu, J. Chen, Laser linewidth tolerance of decision-aided maximum likelihood phase estimation in coherent optical M-ary PSK and QAM systems, *IEEE Photon. Technol. Lett.*, vol. 21, pp. 1075 –1077, Aug. 2009.

[8] J. H. Ke, *et al.*: Linewidth-tolerant and low-complexity two-stage carrier phase estimation for dual-polarization 16-QAM coherent optical fiber communications, *J. Lightwave Technol.*, vol. 30, pp. 3987 – 3992, Dec. 2012.

[9] D.-S. Ly-Gagnon, *et al.*: Coherent detection of optical Quadrature phase-shift keying signals with carrier phase estimation, *J. Lightwave Technol.*, vol. 24, pp. 12 – 21, Jan. 2006.

[10] I. Fatadin, *et al.*: Laser linewidth tolerance for 16-QAM coherent optical systems using QPSK partitioning, *IEEE Photon. Technol. Lett.*, vol. 22, pp. 631 – 633, May. 2010.

[11] Y. Gao, *et al*: Low-complexity two-stage carrier phase estimation for 16-QAM systems using QPSK partitioning and maximum likelihood detection, *in OFC/NFOEC 2011*, Mar. 2011, paper OMJ6.

[12] T. Pfau, *et al.*: Hardware-efficient coherent digital receiver concept with feedforward carrier recovery for M-QAM constellations, *J. Lightwave Technol.*, vol. 27, pp. 989 – 999, Apr. 2009.