Low-Complexity Two-Stage Carrier Phase Estimation for 16-QAM Systems using QPSK Partitioning and Maximum Likelihood Detection

Yuliang Gao[1, 3], Alan Pak Tao Lau[1], Chao Lu[2], Jian Wu[3], Yan Li[3], Kun Xu[3], Wei Li[3] and Jintong Lin[3]

[1]Photonics Research Center, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[2]Photonics Research Center, Department of Electronic and Information Engineering,
The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[3]Key Laboratory of Information Photonics and Optical communications, Ministry of Education in China,
Beijing University of Posts and Telecommunications, Beijing, China, 100876.
E-mail: eeylgao@polyu.edu.hk

Abstract: A feedforward carrier phase estimation algorithm using a modified QPSK partition approach followed by maximum-likelihood (ML) detection is proposed. Results demonstrate complexity reduction by more than a factor of 2 compared with other techniques.

OCIS codes: (060.4510) Optical communications; (060.1660) Coherent communication; (060.5060) Phase modulation

1. Introduction

Quadrature Amplitude Modulation (QAM) combined with digital signal processing with its higher spectral efficiency has become a promising candidate for future optical transmission networks. However, performance requirements for carrier phase noise compensation become very stringent for QAM signals. Thanks to fast digital signal processors (DSPs), frequency offset and carrier phase noise can be recovered using digital signal processing at the receiver, thus allowing for the use of free running local oscillators (LO).

As real-time realization of DSP for coherent systems has become a central topic, complexity is one of the major concerns for research in advanced DSP algorithms [1]. Various feedforward carrier recovery algorithms for 16-QAM systems have been proposed, such as QPSK partitioning and blind phase search (BPS) techniques [2-4]. For QPSK partition, a linewidth times symbol duration product of 1×10^{-4} is achievable for a bit error rate (BER) of 1×10^{-3}, but this method relies on the use of pilot sequence to eliminate the phase ambiguity and cycle slip problems. On the other hand, BPS demonstrates the best phase noise tolerance according to our knowledge but comes with an expense of high complexity [3]. Although this problem has been relieved by reducing the number of test phases and using subsequent maximum-likelihood detection (BPS/ML) [4], the computation effort still remains relatively high.

In this paper, a low-complexity, feedforward and two-stage carrier phase estimation (CPE) algorithm for 16-QAM is proposed using a modified QPSK partition scheme followed by maximum-likelihood detections (QPSK partition/ML). The tolerance of linewidth and complexity of various CPE algorithms are investigated and compared with each other. We show that the proposed technique can reduce the complexity by more than a factor of 2 without any performance degradation.

2. Low-complexity two-stage carrier phase estimator for 16-QAM systems

Consider a 16-QAM system where the received signal is sampled and processed in a DSP. After CD and possibly nonlinearity compensation, timing recovery, polarization demultiplexing, and resampling to 1 sample/symbol, the n^{th} received symbol can be expressed as:

$$s_n = b_n \exp[j(\theta_n + 2\pi\Delta f n T_s)] + z_n \qquad (1)$$

where $b_n \in \{\pm1\pm j, \pm3\pm3j, \pm1\pm3j, \pm3\pm j\}$ are the 16-QAM symbols, θ_n is the combined phase noise of the transmitter laser and LO, T_s is the symbol duration and z_n is amplified spontaneous emission (ASE) noise generated from inline amplifiers. The phase difference between two adjacent symbols (θ_{n+1}-θ_n) can be modeled as zero-mean Gaussian random variable with variance $\sigma^2=2\pi\Delta\nu\cdot T_s$ where $\Delta\nu$ is the combined linewidth of the transmitter lasers and LO.

The partitioning of square 16-QAM symbols for the QPSK partition scheme is shown in Fig. 1 where symbols are classified into three rings Class I (C_1), Class II (C_2) and Class III (C_3) according to their amplitudes. In the inner and outer rings, C_1 and C_3 symbols are two QPSK constellation sets with different optical signal-to-noise ratios (OSNRs). Their modulated phase can be eliminated by Viterbi and Viterbi phase estimation (VVPE) [5]. The block diagram of the proposed algorithm is shown in Fig. 2 (a).

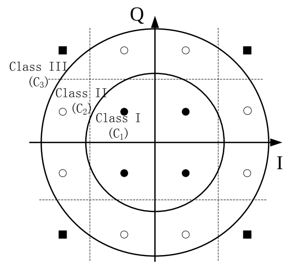

Fig. 1. Partition for 16-QAM signals

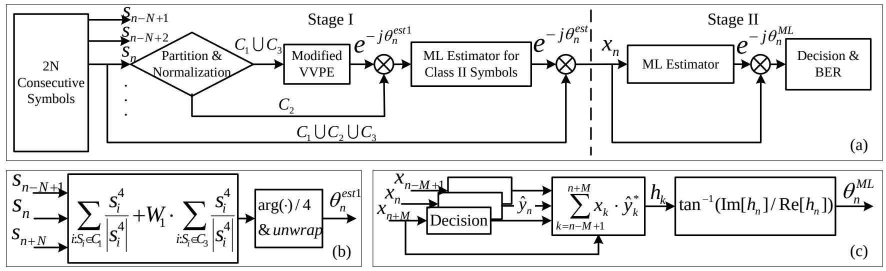

Fig. 2. (a)Block diagram of the proposed algorithm; (b) Modified VVPE; (c) ML Estimator.

The input symbols are first partitioned and normalized according to their amplitudes. If s_n belongs to Class I symbols (C_1) or Class III symbols (C_3), they are first selected to be processed by a modified VVPE [6] to obtain the first phase estimate θ_n^{est1}. The carrier phase estimate can be expressed as

$$\theta_n^{est1} = \frac{1}{4} \cdot \left\{ \sum_{i:s_i = C_1} \frac{s_i^4}{\left|s_i^4\right|} + W_1 \cdot \sum_{i:s_i = C_3} \frac{s_i^4}{\left|s_i^4\right|} \right\} \tag{2}$$

where W_1 is a weighting coefficient which takes into account the fact that symbols in C_3 have a higher OSNR and hence carrier phase estimates from these symbols should be better than those from C_1. Afterwards, the symbols in C_2 are first compensated with the estimated phase θ_n^{est1} and the compensated symbols together with their decisions are fed into an maximum likelihood phase estimator, to obtain a residue phase error θ_n^{est2}. This is then combined with θ_n^{est1} to obtain a more accurate phase noise of the first stage $\theta_n^{est} = \theta_n^{est1} + W_2 \cdot \theta_n^{est2}$, where W_2 is another weight coefficient related to the proportion of symbols in the 2N block that belong to C_2 and relative OSNRs among different classes of symbols. To obtain further accuracies, the recovered symbols at the output of the first stage x_n are again fed into a second stage ML estimator shown in Fig. 2 (c). The ML estimation of the carrier phase θ_n^{ML} can be described as

$$h_n = \sum_{k=n-M+1}^{n+M} x_k \cdot \hat{y}_k^* \tag{3}$$

$$\theta_n^{ML} = \tan^{-1}(\mathrm{Im}[h_n] / \mathrm{Re}[h_n]) \tag{4}$$

where $\hat{y}_k$ is the decision of x_k and 2M is the block length used in the stage II ML estimator.

3. Simulation results and discussion

Simulation results for 16-QAM signals with different linewidths and OSNRs using QPSK Partition, BPS, BPS/ML and the proposed technique are shown in Fig. 3 and 4. To make a fair comparison, we modified the QPSK partition method to be differential encoded, thus avoiding the need of pilot symbols. The weights W_1, W_2 and filter widths are optimized numerically for the proposed QPSK Partition/ML and improves the $\Delta\nu \cdot T_s$ tolerance by about 1dB to 1×10^{-4} for a BER of 1E-3. Also, QPSK partition/ML has the best performance among all techniques for $\Delta\nu \cdot T_s$ larger than 2×10^{-4}. The performance of QPSK Partitioning [2] is noticeably worse than others. Fig. 4 shows the empirical distribution of the residual phase errors using the proposed technique, BPS/ML and BPS with $\Delta\nu \cdot T_s=5\times10^{-4}$. It can be seen that when the $\Delta\nu \cdot T_s$ is as large as 5×10^{-4}, variance of phase error for QPSK partition/ML, BPS/ML and BPS are 3.99×10^{-3} rad^2, 5.56×10^{-3} rad^2 and 5.93×10^{-3} rad^2 respectively, thus indicating the improved performance of the proposed technique.

The required processing complexity for the proposed QPSK Partition/ML scheme can be derived from Fig. 2. Here, we discuss the required operations for 2N symbols. In the partition and normalization block, 2N look-up tables, 4N complex multipliers together with 2N selectors are required. In the following modified VVPE, the N symbols in C_1 or C_3 (on average) require 2N complex multipliers, N-1 complex adders, 1 real multipliers and 1 look-up table to compute θ_n^{est1}. While in the first ML estimator, N complex multipliers, N-1 complex adders, N decision blocks, and 1 look-up table are needed. Since the second ML estimator is supposed to process twice as many symbols in the first one, its complexity is also doubled. Beside these four main blocks there are several simple operations: 3 compensation rotations (5N complex multipliers and 3 look-up tables), 2 weighting operations (only 2 real multipliers) and 1 unwrapping (1 comparator and 1 real adder).

OMJ6.pdf

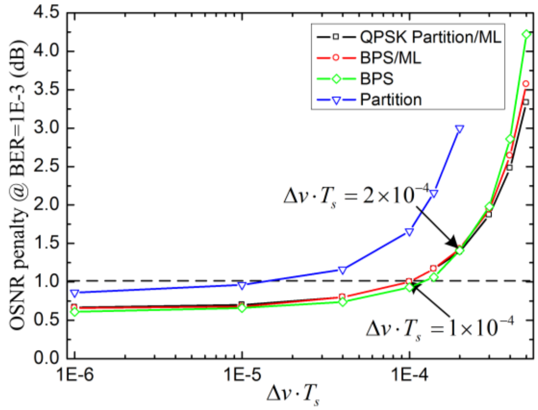

Fig. 3. OSNR penalty versus $\Delta v \cdot T_s$ for various CPE algorithms

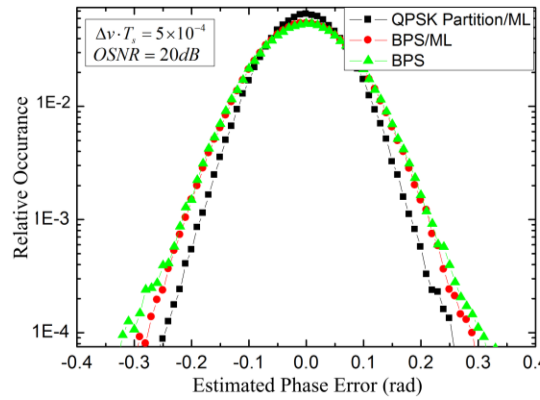

Fig. 4. Empirical distribution of the residual error of CPE algorithms $\Delta v \cdot T_s$ is 5×10^{-4} while the OSNR is 20dB

Table 1. shows the complexity comparisons of the various feedforward algorithms studied in this paper. When discussing the complexity in comparison with the BPS/ML and BPS schemes, we assume 14 and 32 test phases respectively for comparable performance for 1dB sensitivity penalty. From Table.1, it can be seen that for various types of operations, the proposed algorithm requires a complexity that is less than one half and one fourth of BPS/ML and BPS CPE techniques respectively. Although the QPSK partition method is slightly simpler, its performance is noticeably worse than the proposed technique and others studied.

Table 1. Complexity comparison of various carrier recovery techniques for 16-QAM systems

Methods	complex multipliers	real multipliers	decisions	real adders	selectors	look-up table	comparators
QPSK Partion	14*N*	1	2*N*	4*N*-2	3*N*	2*N*+2	*N*+1
QPSK Partition/ML	14*N*	2	5*N*	8*N*-7	2*N*	2*N*+6	1
BPS/ML	32*N*	-	30*N*	32*N*+12	28*N*	29*N*	14
BPS	64*N*	-	64*N*	64*N*	64*N*	64*N*	32

4. Conclusions

A low-complexity feedforward carrier phase estimation algorithm for intradyne coherent systems using modified QPSK partition and ML detection is proposed. Results show that for the same linewidth tolerance, the computational complexity of the proposed technique is at least a factor of 2 lower than others reported in the literature and hence favors future real-time implementation of advanced feedforward carrier phase estimation techniques. In addition, our proposed technique is more tolerant towards phase noise when symbol duration times linewidth is larger than 2×10^{-4}.

References

[1] Z. Tao, L. Li, A. Isomura and J. C. Rasmussen, "Multiplier-free Phase Recovery for Optical Coherent Receivers" in *OFC/NFOEC*, 2008, paper OWT2.
[2] I. Fatadin, D. Ives and S. J. Savory, "Laser Linewidth Tolerance for 16-QAM Coherent Optical Systems using QPSK Partitioning", *IEEE Photonics Technology Letters*, vol. 22, no. 9, pp. 631-633, 2010.
[3] T. Pfau, S. Hoffmann, and R. Noe, "Hardware-efficient coherent digital receiver concept with feedforward carrier recovery for M-QAM constellations," *J. Lightw. Technol.*, vol. 27, no. 8, pp. 989-999, Apr. 15, 2009.
[4] X. Zhou, "An Improved Feed-Forward Carrier Recovery Algorithm for Coherent Receivers with M-QAM Modulation Format", *IEEE Photonics Technology Letters*, vol. 22, no. 14, pp. 1051-1053, 2010.
[5] 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, 1983.
[6] Y. Gao, Y. Cao, Y. Li, J. Wu, K. Xu, W. Li, X. Hong, H. Guo and J. Lin, "A Novel Weighted Feed Forward Digital Carrier Phase Estimation Algorithm for 16-QAM Transmission" in APMP, 2010, paper MB 1-1.