Low-Complexity, Blind Phase Recovery for Coherent Receivers Using QAM Modulation

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Abstract: We propose a new hybrid PLL/ML phase estimation method for low-complexity, blind phase recovery for M-QAM modulation. The linewidth tolerance of the proposed method is more than one order of magnitude better than PLL-only method.

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Introduction

Digital coherent detection coupled with the use of high-order M-ary quadrature amplitude modulation (QAM) plus polarization multiplexing is a promising method to further improve spectral efficiency for future high-speed transmission. To implement M-QAM with M≥16, one major challenge in the optical coherent receiver is accurate phase recovery. Although the decision-directed phase-locked loop (DD-PLL) has been widely used in wireless QAM systems for carrier synchronization, its tolerance to laser phase noise is poor due to its inherent feedback processing delay. Such a processing delay is greatly increased with parallel processing typically required in high-speed optical systems [1]. For quadrature phase shift keying (QPSK), the m^{th}-power-based, feedforward, blind phase-recovery algorithm is well known and several modified Mth-power algorithms have been proposed for M-QAM [2-5]. However, these algorithms either have lower linewidth tolerance [2,4] or can only be applied to 16QAM [3,5]. It has been shown that the minimum distance estimation (MDE) based, blind phase search method (BPS) can achieve nearly optimal laser-linewidth suppression [1]. However the implementation complexity of this method is very high. To address the complexity issue, we recently proposed a hybrid BPS and maximum likelihood (ML) phase estimation method, and with this method we numerically demonstrated a complexity reduction by more than a factor of 3 for square 64QAM [6]. To implement the DD-PLL in high-speed optical systems, a block-processing-based superscalar parallelization scheme [7] has recently been proposed. However, because the DD-PLL operates on a block by block basis, this method requires a very large number of buffer units, as well as a training sequence at the beginning of each data block for initial acquisition.

In this paper we propose a new low-complexity, blind phase recovery method for M-QAM by employing a DD-PLL for coarse phase recovery and one or two ML estimators for phase fine-tuning. We show that the proposed new method can improve the linewidth tolerance by more than one-order of magnitude compared to PLL-only phase recovery, and therefore the new method can be applied to high-speed optical systems employing parallel processing. With a parallelization degree P=16 and PLL processing delay D=5, we demonstrate experimentally that the proposed new method can achieve the same BER performance as the BPS method for a 9.4Gbaud 64QAM system by using standard commercial ECL lasers with a specified maximum linewidth ~100kHz, while the implementation complexity is reduced by a factor of >15.

Algorithm and Implementation Complexity

In the proposed new method we use a DD-PLL implemented with the common interleaving parallelization scheme for coarse phase recovery, followed by a more accurate phase estimate performed by one or two ML phase estimators. The schematic illustration of the proposed method is shown in Fig. 1, where x_k denotes the received signal at one sample per symbol, and a_k denotes the decided/sliced signal following a DD-PLL-based coarse phase recovery. A detailed illustration of the DD-PLL using the common interleaving parallelization scheme is also shown in Fig. 1, were g is the loop parameter. If the error ratio of a_k is not too high, then a_k can be used as a reference signal for a more accurate ML phase estimation given by $\varphi_k^{ML} \approx \arg\left\{ \sum_{n=k-L/2+1}^{n=k+L/2} \left[x_n a_n^* \right] \right\}$ [8], where L denotes the phase smoothing filter length (a ML estimator is essentially a weighted smoothing filter). The decided signal following this improved phase recovery, i.e. a_k^{ML1}, can be fed into a second (or third) ML estimator (MLE) to further refine the phase estimation. Because both the DD-PLL and MLE are applicable to any QAM modulation format, the proposed method can be used as a universal blind phase recovery algorithm for the digital coherent receivers.

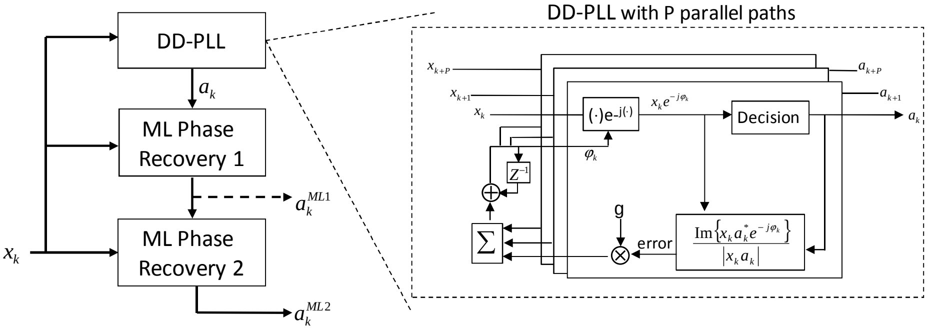


Fig.1. Schematic illustration of the proposed hybrid PLL/ML phase recovery algorithm

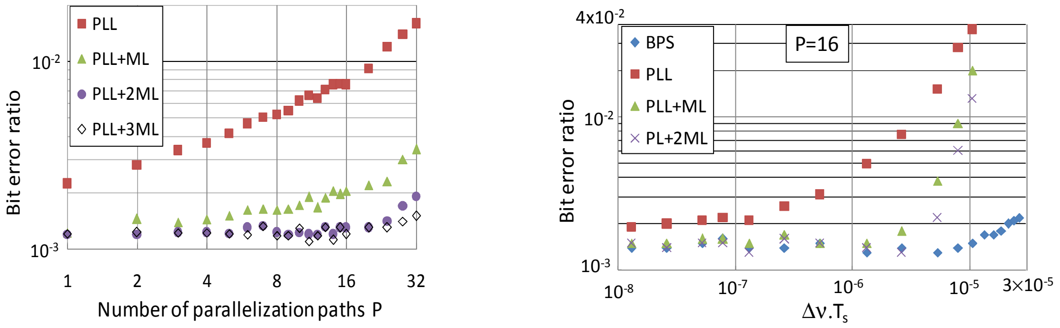
The required hardware implementation complexity of the proposed method along with the BPS and the superscalar parallelization method is given in Table 1. The number of the overall real-number multipliers for BPS is 6.B.P, where the periods denote multiplication, B is the number of trial phases, and P is the number of parallelization paths. For the DD-PPL and MLE the overall real-number multipliers are 9.P and 8.P, respectively. Thus only 17.P multipliers are required for the proposed new method using one MLE. The number of multipliers increases to 25.P when using two MLEs. Such numbers are substantially lower than the BPS method for high-order QAM. For example, to approach an optimal performance, the BPS method requires at least 96.P multipliers for 16QAM and 384.P for 64QAM [1]. One can see that the proposed new method can reduce the number of multipliers by a factor of 4 for 16QAM and a factor of 15.3 for 64QAM. As can be seen from Table 1, the BPS method also requires significantly more real number adders and buffer units than the proposed new method. Compared to the superscalar parallelization method, although the proposed method requires 8 or 16 more real multipliers for each parallelization path, the required memory size is significantly less than the superscalar parallelization method (tens of buffer units versus thousands of buffer units per each parallelization path).

	BPS, Interleaving	DD-PLL, Superscalar	DD-PLL+1 MLE, Interleaving	DD-PLL+2 MLEs, Interleaving
Real multiplier	**6.B.P**	**6.P to 9.P**	**17P**	**25P**
Real adder	(2L-1).B.P	3.P	3.P+2.(L-1).P	3.P+4.(L-1).P
Slicer	B.P	P	2.P	3.P
Memory	L.B.P	2.S.P, S=block length	L.P	2.L.P
Other	P comparators		P arg()	2.P arg()

Table 1. Implementation complexity analysis for several phase recovery schemes.
B: number of trial phases; P: number of parallelization paths; L: length of phase smoothing filter.

Performance

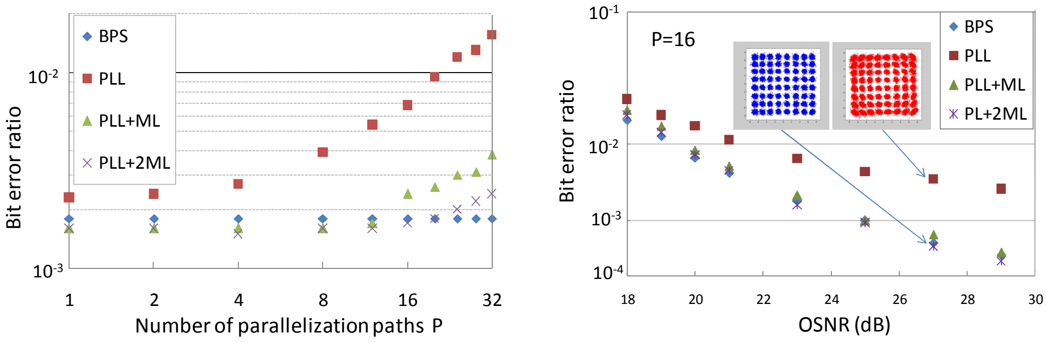
The effectiveness of the proposed method has been verified by both numerical simulation and experiment using a square 64QAM modulation. In Fig. 2 we show the simulated results for a 38Gbaud 64QAM system (only single polarization considered here) operating at an OSNR level of 25dB. For this simulation, the square 64QAM signal is generated by driving an ideal I/Q optical modulator with two eight-level electrical signals obtained by combining three de-correlated 2^{11} De Bruijin binary bit sequence, non-return-to-zero (NRZ) signals. The receiver electrical filter is modeled as a fifth-order Bessel filter with a 3-dB single-side bandwidth equal to 0.55×symbol rate. The frequency offset between the signal source and the local oscillator (LO) is assumed to be zero to focus our attention on the problem of phase recovery. The signal entering the carrier phase recovery module is sampled at one sample per symbol. An adaptive equalizer based on a cascaded multi-modulus algorithm [9] (using 2 samples per symbol, fractionally spaced) has been employed prior to the carrier phase recovery module to equalize the receiver filtering effects. The phase-locked-loop loop parameter and the phase smoothing filter length have been optimized for each simulation. The PLL processing delay D is assumed to be 5 throughout this paper. The BER is calculated based on 6.0×10^5 bits of information. By assuming a laser linewidth of 100kHz, in Fig. 2(a) we show the simulated BER versus the parallelization degree P for different phase recovery schemes. One can see that the proposed method with two MLEs allows the system to operate with more than 16 parallelization paths, whereas the PLL-only method cannot be used for the system even with P=1. For P=16, in Fig. 2(b) we show the simulated BER versus the product of the laser linewidth and symbol period for four different phase recovery scenarios. The linewidth tolerance of the proposed method is more than one order of magnitude better than PLL-only method.



(a) (b)

Fig. 2. Simulated results for a 38Gbaud square 64QAM system, where (a) shows the BER performance under different degrees of parallelization for a laser linewidth of 100kHz, and (b) shows the linewidth tolerance performance. PLL delay D=5 in all simulations.

The effectiveness of the proposed method has also been tested in a 9.4Gbaud 64QAM (single polarization) back-to-back experiment. The 64-QAM optical signal is generated by driving an IQ modulator with a 9.4Gbaud 64QAM baseband signal (pseudorandom pattern length of 2^{15} by using a De Bruijin sequence) obtained from a commercial arbitrary waveform generator. Polarization- and phase-diverse intradyne detection is employed at the receiver. We use standard commercial ECL semiconductor lasers with specified maximum linewidth ~100kHz as the LO and the signal source. The sampling and digitization function is performed by a 4-channel real-time sampling scope with 50 GSa/s sample rate. The captured data is then post-processed using a desktop computer, where the equalization is accomplished using a multi-modulus algorithm [9]. A decision-directed LMS algorithm is not employed in this experiment to reduce the size of parameter space for optimization. The frequency offset between the LO and signal is estimated using a constellation-assisted blind frequency search method, and errors are counted over 1.0 $\times10^{6}$ bits of information. A more detailed description of the experimental setup can be found in [10].



(a) (b)

Fig. 3. Experimental results for a 9.4Gbaud 64QAM system, where (a) shows the BER performance for different degrees of parallelization with 23 dB OSNR and (b) shows the BER performance at different OSNR levels. PLL delay D=5.

In Fig. 3(a) we show the impact of parallel processing on the proposed algorithms for a constant 23dB OSNR. We observe that the proposed algorithm with two MLEs can achieve the same BER performance as the BPS method for P up to 20. The BER performance versus OSNR level for P=16 is given in Fig. 3b. One can see that the proposed algorithm can achieve performance similar to the BPS method for a wide range of OSNR levels with BER ranging from 2×10^{-2} to close to 10^{-4}.

Conclusions

We have proposed a new hybrid PLL/ML phase recovery method for M-QAM modulation formats. Through both numerical simulation and measurements of high-speed optical systems employing parallel processing, we show that, compared to the BPS method, the proposed method has similar performance at significantly lower implementation complexity.

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