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Introduction

The need to increase spectral efficiency in coherent optical transmission systems has led to significant interest in high order quadrature amplitude modulation (QAM) formats. One of the difficulties associated with dense modulation formats is their sensitivity to phase noise, and carrier phase estimation (CPE) has become an increasing problem. Blind CPE algorithms, such as the Viterbi and Viterbi algorithm¹, are unsuitable for systems employing dense modulation formats. Consequently, a variety of approaches for CPE have been proposed. The blind phase search (BPS) algorithm² provides excellent performance but at very high computational cost. Alternatively, low complexity feedback only decision-directed CPE (DD-CPE)³ requires sequential processing on a symbol-by-symbol level. A two-stage approach⁴ has been studied recently, first coarsely estimating the phase with one algorithm and then after phase unwrapping refining the estimates with a more accurate method. Machine learning methods such as particle filtering⁸ for amplitude and phase noise estimation have also been recently explored.

In this paper, we analyze the performance of our recently proposed multi-pilot aided CPE algorithm⁵. This method is based on statistical inference, is of moderate complexity, and is suitable for block-based parallel implementation in hardware. We test this method with DP-64QAM and DP-256QAM via simulations and experiments.

Multi-Pilot CPE Algorithm

We assume all channel impairments except phase noise are compensated and the received signal at discrete time \( n \) is given by

\[
y_n = x_n e^{j \theta_n} + v_n, \quad v_n \sim \mathcal{C}{\mathcal{N}}(0, \sigma^2),
\]

where \( x_n \) is the transmitted symbol, \( \sigma^2 \) is the variance of the additive Gaussian noise and \( \theta_n \) is the phase noise modeled as a Wiener process, i.e.,

\[
\theta_n - \theta_{n-1} \sim \mathcal{N}(0, \sigma^2_p), \quad \sigma^2_p = 2 \pi \Delta \nu T_s, \tag{2}
\]

where \( \Delta \nu \) is the combined laser linewidths and \( T_s \) is the symbol duration.

The pilot symbols aiding CPE are uniformly inserted into the data sequence every \( N \) information symbols. The multi-pilot CPE algorithm estimates the phase of an information symbol by employing \( K \) pilots preceding and \( K \) pilots following that symbol. An example for \( K = 2 \) is shown in Fig. 1, where CPE of information symbols between pilots \( p_2 \) and \( p_3 \) is performed with the aid of pilots \( p_1 \), \( p_2 \), \( p_3 \) and \( p_4 \).

A block diagram of the multi-pilot CPE algorithm is shown in Fig. 2. The algorithm starts with approximating the posterior distribution \( p(\theta_{p_k} | x_{p_k}, y_{p_k}) \) of the phase of each pilot with Gaussian distribution whose mean \( \mu_{p_k} \) is the maximum likelihood phase estimate and the variance \( \sigma^2_{p_k} \) is approximated as an observed Fisher information⁵. The initial phase estimates are then smoothed by accounting for phase noise statistics (2). This is achieved by processing the posteriors \( p(\theta_{p_k} | x_{p_k}, y_{p_k}), k = 1, \ldots, 2K \), through a Kalman filter, yielding means and variances of Gaussian posteriors of pilot symbol phases. We note that \( 2K = 4 \) has been used in this paper, minimizing delay and complexity in the Kalman filter.

The phase \( \theta_n \) of the \( n \)-th information symbol in a block is Gaussian distributed, with mean \( \mu_n \) which is directly evaluated from the Gaussian
posteriors corresponding to pilots $p_K$ and $p_{K+1}$.
These means are initial phase estimates and are refined by employing the Expectation Maximization (EM) algorithm on each symbol separately in parallel. The EM routine for the $n$-th information symbol is initialized with $\hat{\theta}_n(0) = \mu_n$. The $k$-th iteration evaluates the likelihood $p(x_n|y_n, \hat{\theta}_n^{(k-1)})$ given the phase estimate $\theta_n^{(k-1)}$ from the previous iteration. The phase $\hat{\theta}_n$ is then updated from the expected value of the transmitted symbol and the received signal $y_n$. Two iterations of the EM algorithm were used. Finally, the phase estimates were filtered with a moving average FIR filter.

**Simulation**
We simulated the variation of required signal-to-noise ratio (RSNR) to achieve a target BER of $10^{-2}$. An additive Gaussian white noise (AWGN) channel was used, with purely Lorenzian phase noise. A comparison is made between the algorithm presented in this work, and the decision-directed carrier phase estimation (DD-CPE) algorithm described in $^3$.

**Experimental Validation**
CPE performance was then validated experimentally in a back-to-back configuration for DP-64QAM and DP-256QAM at 10 Gbd. The experimental setup used is shown in Fig. 6. A pair of digital-to-analog convertors (DACs) operating at 20 GSa/s were used to generate 64QAM and 256QAM signals at 10 Gbd, including 1% pilot symbols. These signals were filtered with a root-raised cosine (RRC) filter with a roll-off factor of 0.1%. After amplification, these signals were applied to an I/Q modulator operating in the linear regime. The optical carrier was generated by an external cavity laser, with a linewidth of 100 kHz. Polarization-multiplexing was emulated passively in the optical domain with a polarization sensitive delay. Noise loading was performed by coupling in a variable power source of amplified spontaneous emission (ASE) noise. A discrete component coherent receiver was used with a bandwidth of 70 GHz, while the local oscillator was an ECL with linewidth of 100 kHz. Quantization was performed using a oscilloscope with 63 GHz bandwidth and 160 GSa/s. Post-processing was then performed offline.

![Fig. 2: Block diagram of the CPE of an information block aided with 2K pilots.](image1)

![Fig. 3: RSNR to achieve target BER of $10^{-2}$ for 64QAM.](image2)

![Fig. 4: RSNR to achieve target BER of $10^{-2}$ for 256QAM.](image3)
Our receiver DSP consisted of conventional deskew and normalization blocks, 4th power in-dyne frequency estimation, and matched RRC filtering. A $2 \times 2$ multiple input multiple output equalizer was used to compensate for polarization rotation, residual intersymbol interference removal and timing phase recovery. The equalizer was initially radially trained for good convergence, before being switched to pilot-aided operation. A constant modulus error term was calculated based on the pilot symbols only, with updating performed using the least mean square algorithm and an error term averaged over 10 pilot symbols. Carrier phase estimation was then performed as previously described. We then calculated bit-wise log-likelihood ratios (LLRs) using a clustering algorithm to account for transmitter distortion. A low-density parity check (LDPC) code with rate 0.78 (28.2% overhead) was then decoded using the sum-product algorithm. We assume the use of an outer hard-decision code with rate 0.93 (7% overhead) and BER threshold of $3 \times 10^{-3}$. The systems under consideration therefore have net bit rates of 86.5 Gb/s and 115.5 Gb/s for DP-64QAM and DP-256QAM respectively. This corresponds to intra-channel spectral efficiencies of 8.65 b/s/Hz and 11.55 b/s/Hz respectively, while the total overhead is 38.6%.

The results of our back-to-back characterization are presented in Fig. 6. We note that both formats exhibit a BER floor – around $3 \times 10^{-4}$ for DP-64QAM and $10^{-2}$ for DP-256QAM. However, it was noted that we were able to achieve error-free LDPC decoding over 65,536 symbols for both DP-64QAM and DP-256QAM at OSNRs of 17 dB and 23 dB respectively. As we have previously noted\(^7\), performance in the high spectral efficiency asymptote may be limited by electrical impairments rather than optical noise. We therefore note that there are OSNR penalties of 1.9 dB and 2.9 dB at the thresholds of DP-64QAM and DP-256QAM respectively.

Conclusions

We have analyzed the performance of multi-pilot aided carrier phase estimation with DP-64QAM and DP-256QAM. We have noted that this algorithm exhibits good performance with moderate complexity and a fully parallelizable structure. Furthermore, we experimentally demonstrated LDPC coded performance back-to-back using 10 Gbd DP-64QAM and DP-256QAM, with transmitter and receiver laser linewidths of 100 kHz, resulting in implementation penalties of 1.9dB and 2.9dB, respectively.

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