Multi-Pilot Aided Carrier Phase Estimation for Single Carrier Coherent Systems

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1. Introduction

The recent development of second and third generation coherent optical transmission systems has been driven by a desire to increase both noise tolerance and spectral efficiency. While first generation coherent systems relied on dual-polarization quaternary phase shift keying (DP-QPSK) [1], which has high phase noise tolerance, this limits spectral efficiency to 4 b/s/Hz, less overheads for coding and framing. This has led to a wide scale adoption of quadrature amplitude modulation (QAM), with multiple levels of signal per quadrature. Cutting-edge experiments are now using DP- 16-, 64-, and 256-QAM modulation. With the increased density of modulation, carrier phase estimation (CPE) has become an increasing problem. These dense modulation formats are sensitive to phase noise, and yet they are unsuited to blind algorithms such as the Viterbi and Viterbi algorithm [3] which was so successful with DP-QPSK systems [2]. This has led to a wide variety in proposed CPE algorithms [4, 5], many of which are decision-directed (i.e. phase due to modulation is removed with one or more symbol decisions in the CPE algorithm). One approach that has generated significant interest in the research community is that of two-stage phase estimation [6, 7]: first, a coarse estimation is made with one algorithm, unwrapped and applied; then a more accurate algorithm is applied to provide a final estimate without the need for symbol-by-symbol unwrapping. Another approach recently developed is using the phase noise statistics inferred from one or more pilot symbols to calculate log-likelihood ratios more accurately for orthogonal frequency division multiplexing (OFDM) signals [8].

In this paper, we propose a two-stage pilot-aided scheme for CPE, suitable for operation in the low SNR regime which is optimal for bit-interleaved coded modulation (BICM). The initial estimate of phase is inferred on a block basis from multiple pilots using Kalman smoothing [9]. This initial estimate is then refined by performing expectation-maximization in parallel for the information symbols in the block. Finally, an averaging filter is used on the phase estimate, before the estimated phase is applied to the signal. These algorithms are of moderate complexity, and are suitable for block-based parallel implementation in hardware. The performance of our proposed algorithm is validated by simulation over the SNR region for which 64-QAM is optimal for bit-interleaved coded modulation.

2. Proposed Algorithm

2.1. Channel and Phase Noise Model

Assuming all signal impairments but phase noise have been compensated, a sample of the received signal at discrete time n, y_n, is modeled as

$$y_n = x_n e^{j\theta_n} + v_n, \quad \text{where} \quad v_n \sim \mathscr{CN}(0, \sigma_v^2), \quad \theta_n - \theta_{n-1} \sim \mathscr{N}(0, \sigma_p^2), \quad \text{and} \quad \sigma_p^2 = 2\pi\Delta v T_s, \tag{1}$$

where x_n is the transmitted symbol chosen uniformly from some constellation $\mathscr{X}$, Δv is the combined linewidths of transmitter's laser and local oscillator, and T_s is the duration of the signaling interval.
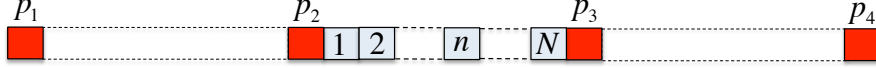
Fig. 1. Illustration of multi-pilot estimation with $2K = 4$ pilots.

2.2. Processing Stage 1: Inference of Pilot Symbol Phases

We assume that N information symbols are transmitted in a block and each block starts with a pilot symbol. To estimate the phase of a symbol transmitted during the n-th signaling interval, K pilots preceding and K pilots following the considered symbol are used. Figure 1 depicts an example where $K = 2$ and phase estimation 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.

The pilot processing stage starts with approximating the posterior distribution $p(\theta_{p_k}|x_{p_k}, y_{p_k})$ of pilot p_k's phase, conditioned on the transmitted symbol x_{p_k} and received signal y_{p_k}. Since direct application of Bayes' rule on model (1) does not admit a closed form expression, we approximate the posterior with Gaussian distribution such that $p(\theta_{p_k}|x_{p_k}, y_{p_k}) \sim \mathcal{N}(\mu_{p_k}, \sigma_{p_k}^2)$, where mean μ_{p_k} is the Maximum Likelihood phase estimate, while the variance $\sigma_{p_k}^2$ is evaluated as an observed Fisher information [9].

The distributions of pilot phases are then smoothed by accounting for phase noise statistics. This is achieved by processing the posteriors $p(\theta_{p_k}|x_{p_k}, y_{p_k})$, $k = 1, \ldots, 2K$, through Kalman filter via full forward pass from pilot p_1 to p_{2K}, and backward pass from pilot p_{2K} to p_{K+1}. On an implementation side, Kalman filter used here can either be realized as a sequential processor over $2K$ scalars, or as a parallel processor which performs inversion of a matrix of size $2K$ on each pilot. Our study shows that increasing the number of pilots $2K$ above some relatively small value, which could be as low as 4 in most scenarios with $\Delta \nu T_s$'s encountered in practice, yields negligible performance gains. Therefore, either implementation of Kalman filtering does not lead to excessive delays or unreasonable increase in required computations.

2.3. Processing Stage 2: Estimation of Information Symbol Phases

The second processing stage starts with inferring phases of information symbols using the Gaussian phase posteriors corresponding to pilots p_K and p_{K+1}, obtained in the previous stage, and phase noise statistics. Omitting the details, it is shown that the information symbol n's phase, θ_n, can be summarized as $p(\theta_n|x_{p_1}, y_{p_1}, \ldots, x_{p_{2K}}, y_{p_{2K}}) \sim \mathcal{N}(\mu_n, \sigma_n^2)$, where μ_n depends on the means and variances of Gaussian posteriors corresponding to pilots p_K and p_{K+1}, obtained at the output of Kalman filter.

The initial estimates μ_n of information symbol phases are refined by employing the Expectation Maximization (EM) procedure on each symbol separately in parallel. The EM routine corresponding to the n-th information symbol is initialized with $\hat{\theta}_n^{(0)} = \mu_n$. The k-th iteration evaluates the likelihood of symbol x_n given the received signal y_n and phase estimate $\theta_n^{(k-1)}$ from the previous iteration. Then, the symbol likelihoods are used to update the corresponding phase estimates. The EM procedure is terminated after some predefined number of iterations. Our study shows that the EM algorithm converges fairly quickly so that after already 2 iterations the performance gains become negligible.

In the final processing step, the EM phase estimates are filtered using a moving average filter, which yields the final phase estimates of information symbols. The soft and hard decisions of the transmitted symbols then directly follow from model (1) and final phase estimates.

3. Simulation Results

In order to determine the appropriate SNR regime for which 64-QAM is optimal, we simulated the Generalized Mutual Information (GMI) [10] for 16-QAM, 64-QAM and 256-QAM over an AWGN channel. The results of this simulation are presented in Fig. 2(a). We noted that 64-QAM is optimal between approximately 10 dB and 17 dB SNR. This corresponds to the range of SNRs for which 64-QAM has the best spectral efficiency of the square-QAM formats, assuming the use of BICM.

We then simulated the performance of 64-QAM, with varying $\Delta \nu T_s$ from 10^{-5} to 10^{-4}. We compared the performance of the D-PLL algorithm presented in [4], with the algorithm proposed in this paper. The results of these simulations are presented in Fig. 2(b) and 2(c) respectively. We note that while the D-PLL algorithm has satisfactory performance at low $\Delta \nu T_s$, it fails rapidly as $\Delta \nu T_s$ is increased beyond 2×10^{-5}. By comparison, our algorithm is remarkably robust in the presence of high levels off additive noise and phase noise. We note that for $\Delta \nu T_s = 10^{-4}$, we
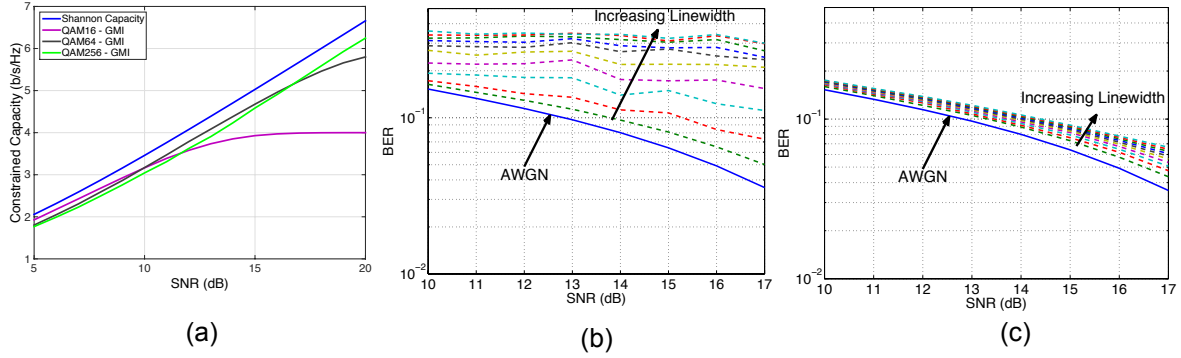
Fig. 2. (a) Capacity of different square QAM modulation formats with AWGN channel, assuming BICM. Performance of 64QAM over the BICM optimal region with AWGN only, and $\Delta \nu T_s$ from 10^{-5} to 10^{-4} is plotted for (b) D-PLL carrier recovery, and (c) our proposed algorithm.

see a penalty of less than 2 dB at a BER of 0.1. This corresponds to an SNR improvement of more than 3 dB over the D-PLL algorithm.

4. Conclusions

We have proposed a pilot aided carrier phase recovery algorithm for single carrier, coherent systems. The algorithm utilizes multiple pilots for estimating phase rotation of an information symbol, relies on statistical inference techniques and admits parallel implementation in hardware. We determined the optimal SNR region for BICM performance of 64-QAM, and demonstrated significant performance improvements compared with the D-PLL algorithm.

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