Maximum-Likelihood Mth Power Carrier Phase Estimation for Coherent Optical Communication

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Abstract: We propose a maximum-likelihod (ML) Mth power carrier phase estimator which is optimized considering the amplitude of received signal. Significant improvement can be achieved compared to conventional Mth power which relies on intuitive nonlinear operations.

OCIS codes: (060.4510) Optical Communications;(060.1660) Coherent Communication

The carrier phase estimation (CPE) preceding the coherent detection is required while using advanced modulation formats, such as M-ary phase shift keying (PSK), amplitude phase shift keying and quadrature amplitude modulation (QAM). The Mth power algorithm introduced by Viterbi & Viterbi is the most popular carrier phase estimator for MPSK [1]. Current variations of the Mth power method focus on intuitive nonlinear operations of the received signal amplitude only [1,2]. The additive observation phase noise (AOPN) due to the additive white Gaussian noise (AWGN), however, is the major noise source for CPE [3]. Using the high SNR approximation of the Tikhonov pdf of AOPN by a Gaussian distribution, which leads to the best linearized AOPN model [3], we propose, for the first time, maximum-likelihood (ML) Mth power carrier phase estimation. To facilitate its implementation, the proposed ML Mth power method is further extended to 16QAM through QPSK partitioning [4].

In this paper, we assume perfect channel estimation and frequency offset compensation. Te laser phase noise and AWGN are considered as the dominant distortions. In this case, the received signal at time k is given as $r(k) = m(k)e^{j\theta(k)} + n(k)$. By raihsing the received signal to its Mth power, the phase modulation can be removed, i.e., $r^M(k) = |r(k)|^M \exp\{jM[\angle m(k) + \theta(k) + \varepsilon(k)]\} = |r(k)|^M \exp\{jM[\theta(k) + \varepsilon(k)]\}$. Term $\varepsilon(k)$ denotes the AOPN term. It has been shown that at high SNR, $\{\varepsilon(l)\}_k$ can be approximated as a sequence of independently distributed Gaussian random variables with mean zero and variance $\sigma_\varepsilon^2(k) = N_0/[2\sqrt{E_s}|r(k)|]$ [3]. We that use the principle argument of $r^M(k)$, denoted as $z(k) = M\theta(k) + M\varepsilon(k)$, as the observations. Based on the Gaussian approximation of $\varepsilon(k)$, it is easy to show that $z(k)$ is also Gaussian distributed with mean of $M\theta(k)$ and variance of $\sigma_z^2(k) = M^2 N_0/[2\sqrt{E_s}|r(k)|]$ conditioned on the unknown carrier phase $\theta(k)$. In this case, the likelihood function, denoted as $\Lambda(k)$, is defined as the joint probability density function (PDF) of $\{z(l)\}_{l=k-L}^{k+L}$ conditioned on $\theta(k)$. Assuming that the carrier phase remains constant within the estimation window, $z(i)$ and $z(j)$ are independent $\forall i \neq j$ due to the inherent independence of the AOPN term. Through maximizing the log-likelihood function $L(k) = \ln \Lambda(k)$, the ML Mth power phase estimation $\hat{\theta}(k)$ can be easily obtained as $\hat{\theta}(k) = \left[\sum_{l=k-L}^{k+L} z(l)/\sigma_\varepsilon^2(l)\right] / [M \sum_{l=k-L}^{k+L} 1/\sigma_\varepsilon^2(l)]$.

From the derivation, the estimation performance of the ML Mth depends on the unwrapping of estimation variable $z(k)$. Similarly, conventional Mth power based on the intuitive nonlinear operations also requires phase unwrapping for the argument extraction. For fair comparison, the genie-aided method is applied for both carrier phase estimators. Denoting the carrier phase estimation error as $e(k) = \theta(k) - \hat{\theta}(k)$, the inverse variance of $e(k)$, defined as $IV = -10\log \mathrm{var}[e(k)]$, is used as the performance metric in our following simulations. The proposed technique is first evaluated in differentially encoded MPSK systems with the transmission bit rate fixed as $R = 50$ GS/s. The IV of carrier phase estimation error is measured as a function of the symbol SNR $\gamma_s = E_s/N_0$ and the laser linewidth $\Delta\nu$ in Fig. 1 (a) and (b), respectively. As shown, Mth power with $F(|r(k)|) = |r(k)|^M$ achieves the worst estimation performance in all tested modulations. Through applying $F(|r(k)|) = |r(k)|^2$ and $F(|r(k)|) = 1$, 2dB improvement can be observed in 8PSK and 16PSK at γ_s of 13dB and 17dB, respectively. In QPSK, the performance enhancement is less significant because of the small M. However, the gain due to the use of different nonlinear operations in conventional Mth power decreases along with the increase of SNR. This is because, at high SNR, the amplitude of the received signal is approximately static. Hence, the effect of $|r(k)|$ is less crucial during the carrier phase estimation. Moreover, as shown in Fig. 1 (a), with small laser linewith $\Delta\nu$ =100kHz, the ML Mth power method gives about the same

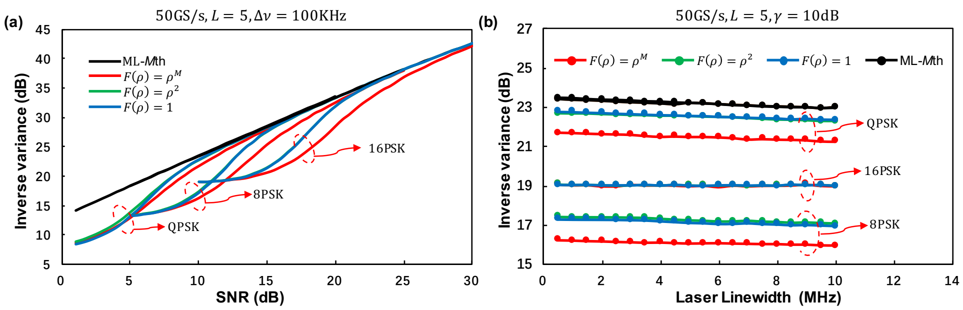

Fig. 1. Performance comparison of ML Mth power phase estimator and conventional Mth power with different nonlinear operations as a function of (a) symbol SNR and (b) laser linewidth.

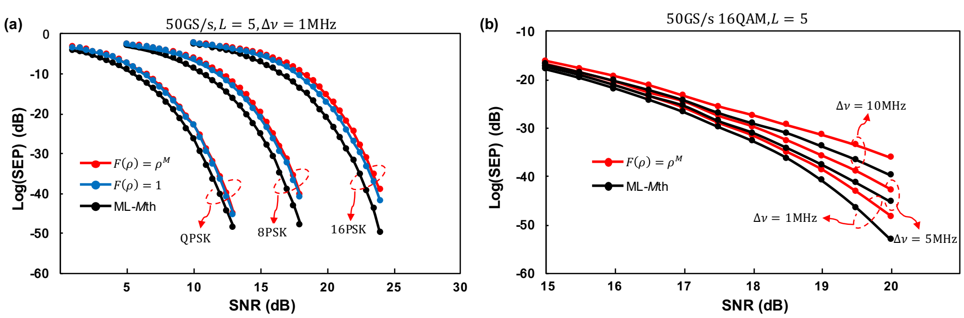

Fig. 2. SEP performance investigation in (a) MPSK and (b) 16QAM modulated systems.

performance as the conventional Mth power at high SNR. However, significant performance improvement can be observed as the SNR decreases. Due to the consideration of the phase noise, as illustrated in Fig. 1 (b), significant performance improvement can be observed by using the ML method at $\Delta\nu$ up to 10MHz.

The symbol error rate (SEP) of the ML Mth power and conventional Mth power is further compared as a function of γ_s. Since the conventional Mth power with $F(|r(k)|) = 1$ achieves the similar accuracy with that using $F(|r(k)|) = |r(k)|^2$, only $F(|r(k)|) = 1$ is tested for comparison. From Fig. 2 (a), approximately the sample performance can be observed by using conventional Mth power with different $F(|r(k)|)$. With the ML Mth power, nearly 1dB improvement can be achieved at SEP of 10^{-4} compared with the conventional Mth power. Through QPSK partitioning, conventional Mth power carrier phase estimator can be implemented in 16QAM modulated systems [4]. The ML Mth power method can be extended to multi-level constellations in a similar way. Here, 16QAM with 3 amplitude levels is selected as an example. Similarly, to eliminate the unexpected distortion due to the phase unwrapping, genie-aided technique is applied during the simulation. In Fig. 2. (b), the SEP is measured as a function of the SNR and the laser linewidth. As shown, despite the assumption of constant carrier phase, the ML Mth power outperform the conventional Mth power by around 0.5dB at SEP of 10^{-4} and $\Delta\nu$ of 5MHz.

Overall, assuming the ideal phase unwrapping, the ML Mth power carrier phase estimator is shown to outperform the conventional Mth power with intuitive nonlinear operations. Although high SNR is assumed in the approximate Gaussian distribution of the AOPN, the ML Mth power still works well at low SNR. Additionally, in spite of the assumption of the constant carrier phase during the derivation, the ML Mth power is applicable in systems with slowly time-varying carrier phase.

The authors would like to gratefully acknowledge the financial support from National Natural Science Foundation of China (Grant 61501313, 61471253, 61571316 and 61302112) and HKPU (Grant 1-ZE5K).

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