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Accurate Laser Linewidth Estimation using the DA-ML Carrier Phase Estimator

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Abstract: An accurate laser linewidth estimation technique is introduced based on the DA-ML phase estimator. Numerical simulations show that our method is constellation independent and applicable within a wide range of laser linewidth and symbol SNR.

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1. Introduction

The characterization of the laser phase noise due to the transmitter and receiver laser attracts extensive investigations. Early researchers relied on the electrical spectrum analyzer for accurate estimation of laser linewidth [1]. Recently, coherent receiver based techniques, which allows time domain digital signal processing, become more popular. Both static and dynamic estimation can be performed using either heterodyne or intradyne receiver [2–4]. Compared with these time domain techniques, machine learning based methods, including extended Kalman and particle filtering, achieve even better estimation accuracy [5].

This paper introduces an accurate laser linewidth estimation based on the decision-aided maximum likelihood (DA-ML) phase estimator [6, 7]. The estimation performance is investigated via numerical simulations.

2. DA-ML based laser linewidth estimation

We assume a laser phase noise dominant channel with perfectly compensated chromatic dispersion, polarization mode dispersion and frequency offset [7]. For simplicity, M-ary phase shift keying (MPSK) is considered here as an example. A canonical model of the received signal is applied, which is given as [7]

$$r(k) = m(k)e^{j\theta(k)} + n(k). \tag{1}$$

Term $m(k)$ denotes the kth transmitted symbol. For MPSK, it takes on values from the signal set $\{S_i = E_s^{1/2} e^{j\frac{2\pi i}{M}}, i = 0, 1, ..., M-1\}$ with equal probability. E_s denote the symbol energy and M is the number of signal points. Term $n(k)$ is a zero-mean, complex, Gaussian random variable with variance N_0, where N_0 is the one-side spectrum of the additive white Gaussian noise (AWGN). Term $\theta(k)$ denotes the laser phase noise at kth symbol, which is commonly modeled as a Wiener process: $\theta(k) = \theta(k-1) + \nu(k)$ [8]. Term $\{\nu(k)\}$ is a set of independent, identically distributed, Gaussian random variables with mean zero and variance $\sigma_p^2 = 2\pi\Delta\nu T$. T and $\Delta\nu$ denote the symbol duration and combined linewidth of transmitter and receiver laser. Obviously, the phase increment $\{\nu(k)\}$ is independent with the AWGN noise $\{n(k)\}$. Regarding the phase of the kth received symbol, we can easily find [9]

$$\angle r(k) = \phi(k) + \theta(k) + \varepsilon(k) \tag{2}$$

where $\phi(k) = 2\pi i/M, \{i = 0, 1, ..., M-1\}$ denotes the phase modulation. Term $\varepsilon(k)$ is the additive observation phase noise (AOPN) due to $n(k)$. For high SNR $\gamma = E_s/N_0$, ε is approximately Gaussian distributed with mean zero and variance $\sigma_\varepsilon^2 = 1/2\gamma$ [10]. The DA-ML phase estimation method is first derived in [6]. Assuming slowly varying phase noise, L previous symbols are applied to estimate the current phase, where L is called the estimation window length. Assuming perfect hard decisions of previous symbols, the DA-ML estimation $\hat{\theta}(k)$ of the phase noise $\theta(k)$ is [6]

$$\hat{\theta}(k) = \angle\left[\sum_{l=k-L}^{k-1} r(l)\hat{m}^*(l)\right]. \tag{3}$$

Here, $\hat{m}(l)$ is the receiver decision of the lth symbol. Due to a finite SNR in real applications, DA-ML phase estimator would inevitably lead to a phase reference error (PRE) defined as $\theta_e(k) = \theta(k) - \hat{\theta}(k)$. In [7], θ_e is shown, for high γ, to be approximately Gaussian distributed with mean zero and variance

$$\sigma_e^2 = \frac{2L^2+3L+1}{6L}\sigma_p^2 + \frac{1}{2\gamma L}. \tag{4}$$

To estimate the laser linewidth, we define a phase difference parameter $\omega(k)$ as

$$\omega(k) = \angle r(k) - \hat{\theta}(k) - \angle \hat{m}(k). \tag{5}$$

Supposing accurate hard decisions, we have $\angle \hat{m}(k) = \phi(k)$. Substituting (2) into (5), $\omega(k)$ can be simplified as

$$\omega(k) = \phi(k) + \theta(k) + \varepsilon(k) - \hat{\theta}(k) - \angle \hat{m}(k) = \theta_e(k) + \varepsilon(k). \tag{6}$$

In (6), $\theta_e(k)$ depends on the phase noise $\theta(k)$ and DA-ML estimation $\hat{\theta}(k)$ of kth symbol. As aforementioned, $\theta(k)$ consists of previous phase noise $\theta(k-1)$ and current phase increment $\nu(k)$, where both terms are independent with current AWGN noise $n(k)$. Based on (3), $\hat{\theta}(k)$ is a function of the previous measurements up to $(k-1)$th symbol, which is also independent with $n(k)$. Since $\varepsilon(k)$ in (6) is defined based on $n(k)$, $\theta_e(k)$ and $\varepsilon(k)$ are statistically independent. Therefore we can conclude that, ω given in (5) is also Gaussian distributed with mean zero and variance

$$\sigma_\omega^2 = E[\omega(k)^2] = \sigma_e^2 + \sigma_\varepsilon^2 = \frac{2L^2+3L+1}{6L}\sigma_p^2 + \frac{L+1}{2\gamma L}. \tag{7}$$

Through inverting (7), σ_p^2 can be expressed as a function of γ, L and σ_ω^2 given as

$$\sigma_p^2 = 6L\left(\sigma_\omega^2 - \frac{L+1}{2\gamma L}\right)/(2L^2+3L+1). \tag{8}$$

During the implementation, the DA-ML technique is applied to estimate the carrier phase of received symbol at first. Then, ω of each symbol is calculated for a long period of time using (5). With the series of measured $\omega(k)$, we further calculate its variance given as $\sigma_\omega^2 = E[\omega(k)^2]$. Assuming known γ, with the calculated σ_ω^2, we can compute the σ_p^2 based on (8), thereby generating an estimation of combined laser linewidth given as $\Delta\nu = \sigma_p^2/2\pi T$.

3. Simulation results and discussions

Assuming perfect decision feedback, the estimation performance of the DA-ML based technique is investigated in MPSK systems. Here, the inverse of the normalized mean square error (NMSE), defined as

$$\mathrm{NMSE} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\hat{\Delta\nu}_i - \Delta\nu}{\Delta\nu}\right)^2, \tag{9}$$

is used as the criterion, where $\hat{\Delta\nu}_i$ is the ith estimation of $\Delta\nu$ and N is the number of estimations used for each calculation of the NMSE. In Fig. 1, the estimation performance for different modulations are approximately the same as expected. In addition, the measured inverse NMSE improves with the increasing γ. This is because that the PRE variance given in (4) is derived based on the assumption of high SNR. Moreover, Fig. 1 (b) shows that larger $\Delta\nu$ leads to better estimation accuracy. With small $\Delta\nu$, σ_ω^2 in (7) would be too small to be accurately estimated.

The effect of L on the estimation accuracy and the optimized L for various $\Delta\nu$ are further investigated in 8PSK. In Fig. 2 (a), we can observe a performance improvement of up to 10 dB with L increased from 5 to 10 and 15. The cross point of the inverse NMSE indicates that the optimal choice of L depends on the laser linewidth value. As shown in Fig. 2 (b), there exist an optimal point for each $\Delta\nu$ as expected and the optimal L decreases with the growth of laser linewidth. This is because, with small $\Delta\nu$, long estimation window is preferred to average out the AWGN noise. However, when the system suffers from high level phase noise, long estimation window will conflict with the assumption that the phase noise is approximately constant within an estimation window, thereby degrading the estimation performance.

4. Conclusion

In this paper, an accurate laser linewidth estimation technique based on the DA-ML phase estimator is proposed. Numerical simulations show that our technique is modulation independent and the estimation performance improves with the increase of SNR and laser linewidth value. We further investigate the optimal estimation window length while implementing our method, which can be recognized as a meaningful reference in real applications.

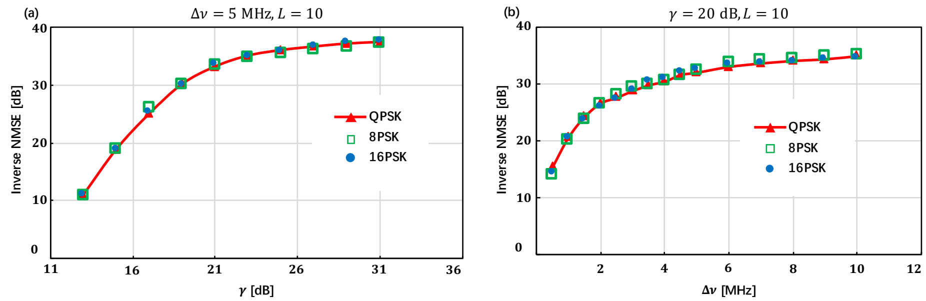

Fig. 1: Inverse NMSE versus (a). symbol SNR γ and (b). combined laser linewidth $\Delta\nu$, with symbol rate $R = 50$ GS/s.

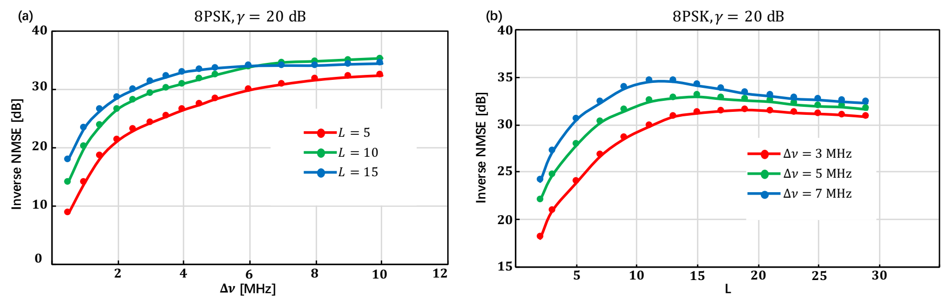

Fig. 2: Inverse NMSE versus (a). combined laser linewidth $\Delta\nu$ and (b). estimation window length L, with $R = 50$ GS/s.

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