Joint Compensation of Frequency Offset, Phase and Amplitude Noise Using Two Stage Extended Kalman Filtering

Lalitha Pakala*, Bernhard Schmauss
Institute of Microwaves and Photonics (LHFT) and Erlangen Graduate School in Advanced Optical Technologies (SAOT), University of Erlangen-Nuremberg, Cauerstrasse 9, 91058 Erlangen, Germany, *lalitha.pakala@fau.de.

Abstract

We propose a two stage extended Kalman filtering (EKF) for the joint tracking of frequency offset (FO) and phase noise with simultaneous amplitude noise mitigation. In the first stage, an EKF has been employed for a coarse estimation of the frequency offset using a set of training data symbols. The EKF employed in the second stage will compensate for the residual FO along with phase and amplitude noise. The performance of the EKF has been compared to a two stage linear Kalman filtering (LKF) for polarization multiplexed (PM) 16-quadrature amplitude modulation (QAM) system operating at 28 Gbaud. Numerical results justify that our proposed two stage EKF approach outperforms the LKF with improved tolerance towards FO, phase and amplitude noise.

1 Introduction

The advent of coherent detection and digital signal processing (DSP) has made it possible to achieve data rates of 100-Gbit/s and beyond, while the standardization of 400-Gbit/s Ethernet transmission is under active development [1-3]. In a standard coherent receiver, DSP module including chromatic dispersion (CD) compensation, polarization de-multiplexing, carrier phase estimation (CPE) has become mandatory for the digital equalization of fiber transmission impairments [4]. Moreover, modern coherent receivers run with a free local oscillator (LO), and therefore, digital carrier synchronization is one of the important DSP modules to compensate the frequency and phase deviation between the transmitter laser and LO. The commonly employed CPE algorithms have low tolerance to the frequency offset (FO) between the transmitter laser and LO which may go as high as $\pm$ 5 GHz [5-6]. Consequently, many FO estimation algorithms have been proposed which can be classified into two categories that are either based on the phase increments between adjacent symbols [7] or spectrum based methods [8]. Recently, Kalman filtering has attracted much attention with its potential capability to mitigate several optical transmission impairments simultaneously [9-12]. The FO estimation schemes using Kalman filtering have been proposed in [12] and [13]. In [12], it has been presented that the Kalman filter can achieve faster convergence and shows an improved performance over conventional FO estimation at low optical signal to noise ratios (OSNR). Several FO estimation schemes based on blind and training data methods using linear and extended Kalman filtering (EKF) for quadrature phase shift keying (QPSK) systems have been presented in [13].

In this work, we propose a two stage EKF for the joint compensation of FO, phase noise and amplitude noise. In the first stage, a coarse estimate of FO has been obtained by using a set of training data symbols as proposed in [13]. In the second stage, we employ our proposed carrier phase and amplitude noise estimation (CPANE) [9-10] algorithm to compensate the residual FO, phase and amplitude noise in the decision directed mode. The coarse compensation of FO in the first stage will improve the phase estimation accuracy during the second stage and the remaining small amount of residual FO can be jointly estimated along with the phase noise. We also employ a similar two stage approach based on linear Kalman filtering (LKF). The performance of the considered methods have been verified for the back-to-back (BTB) configuration of a 28 Gbaud polarization multiplexed (PM) 16-quadrature amplitude modulation (QAM) system. Numerical results show that our proposed EKF method outperforms the LKF with better tolerance towards FO and phase noise besides amplitude noise.

2 Principle of two stage EKF

The received signal after linear equalization for single polarization, can be modeled as given in Eq. (1). Here, $r(k)$ and $a(k)$ denote the received and the transmitted signal at the k-th time instant. ω denotes the FO between the transmitter laser and the LO, T_s denotes the symbol duration, $\phi(k)$ denotes the phase noise and $n(k)$ denotes the additive white Gaussian noise (AWGN).

$$r(k) = a(k)\mathrm{e}^{j(\omega k T_s + \phi(k))} + n(k) \tag{1}$$

$$m(k) = \mathrm{e}^{j(\omega + v(k))} + \eta(k) \tag{2}$$

$$\theta(k) = \omega + v(k) + \xi(k) \tag{3}$$

After wiping off the data phase using training data and normalizing the amplitude modulation, the measured FO of ω, denoted by $m(k)$, which corresponds to the phase difference between two adjacent symbols [13], is given in Eq. (2). The FO measurement can also be obtained by taking the argument of Eq. (2) and can be expressed in the linear form, denoted by $\theta(k)$ as given in Eq. (3). Here, $v(k)$ is given by $v(k) = \phi(k) - \phi(k-1)$, and can be assumed to be

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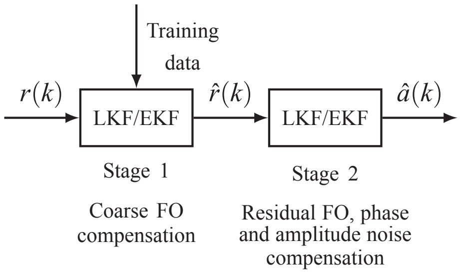

Figure 1 Block diagram of two stage LKF/EKF for the joint compensation of FO, phase and amplitude noise.

zero mean Gaussian distribution with variance of $2\pi\delta\nu T_s$, where $\delta\nu$ is the sum of laser linewidths of the transmitter and LO, $\eta(k)$ and $\xi(k)$ can be assumed to be AWGN. By considering the observation models in Eq. (2) and Eq. (3) for EKF and LKF, respectively, a coarse FO estimate can be obtained by using a set of training data symbols. After a coarse FO compensation in the first stage, the received signal can be represented as given in Eq. (4).

$$\hat{r}(k) = a(k)e^{j(\triangle\omega(k)+\phi(k))} + n(k) \tag{4}$$

Here, $\hat{r}(k)$ denotes the received signal after the first stage FO compensation and $\triangle\omega(k)$ denotes the residual FO. For the joint tracking of residual FO, phase and amplitude noise, in the second stage, we implement CPANE algorithm using EKF, and the state estimate is a complex quantity which facilitates for the compensation of amplitude noise also. In case of LKF, the observation model can be obtained by taking the argument of Eq. (4) for the joint tracking of residual FO and phase noise. In the second stage, both LKF and EKF are run in the decision directed mode. The block diagram illustrating the two stage structure of LKF (for the joint compensation of FO and phase noise) / EKF (for the joint compensation of FO, phase and amplitude noise) is depicted in Fig. 1.

3 Numerical Results

In order to assess the performance of the two stage EKF and LKF algorithms, numerical simulations were performed on a 28 Gbaud PM-16-QAM system in BTB configuration. Firstly, to investigate the FO tracking performance alone, the FO between the transmitter and the LO has been set to 1 GHz and the laser linewidth has been set to 0 kHz. The measurement and process noise covariances of LKF and EKF has been set to optimize the performance. In the first stage of FO estimation, the simulations were performed by considering 200 and 500 training data symbols. In order to compare the performance of LKF and EKF after the first stage of FO estimation, the normalized mean square error (NMSE) is computed as $\frac{(\omega-\hat{\omega})^2}{\omega}$. The NMSE vs. OSNR curves for the LKF and EKF after the first stage when handling 200 and 500 training data symbols are depicted in Fig. 2. The simulation results in Fig. 2 illustrates that the EKF outperforms LKF even at low OSNRs with reduced NMSE of an order of magnitude when either 200 or

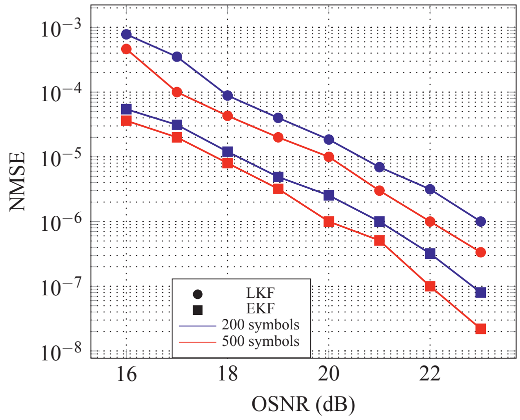

Figure 2 NMSE vs. OSNR curves for LKF and EKF after the first stage of FO estimation for a FO of 1 GHz.

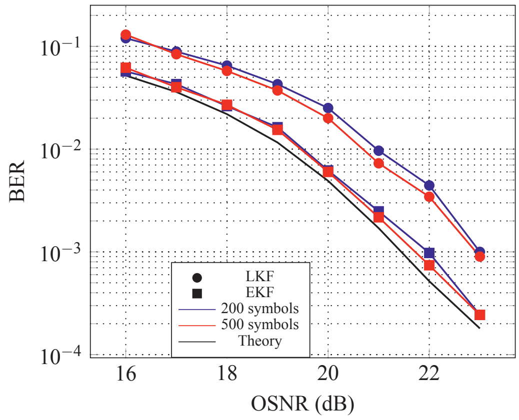

Figure 3 BER vs. OSNR curves for LKF and EKF after the residual FO compensation for a FO of 1 GHz.

500 training data symbols were considered. This can be attributed to the fact that the EKF does not involve any angle operations that might result in additional errors as contrary to LKF and the observation model is more accurate. It can also be observed that by increasing the training data symbols from 200 to 500, there is no significant improvement in the NMSE at low OSNRs which justifies for the faster convergence of both LKF and EKF. After computing the FO estimate using the 200 or 500 training data symbols in the first stage, the signals are further processed through the second stage of LKF and EKF for the residual FO compensation in the decision directed mode. The bit error ratio (BER) vs. OSNR curves for the LKF and EKF after the residual FO compensation are depicted in Fig. 3. The curve denoted by 'Theory' in Fig. 3 represents the BER vs. OSNR curve for the BTB case without FO and phase noise. It can be noticed from Fig. 3 that after the residual FO compensation in the second stage, the number of utilized training data symbols in the first stage does not significantly influence the performance of LKF/EKF, which proves better tracking capability of the residual FO by both LKF and EKF. However, as discussed earlier, EKF outperforms LKF with an improved tolerance towards FO and operates close to the theory curve, whereas, LKF shows a penalty of $\approx$ 2 dB at a BER of 2e-2, compared to the theory curve.

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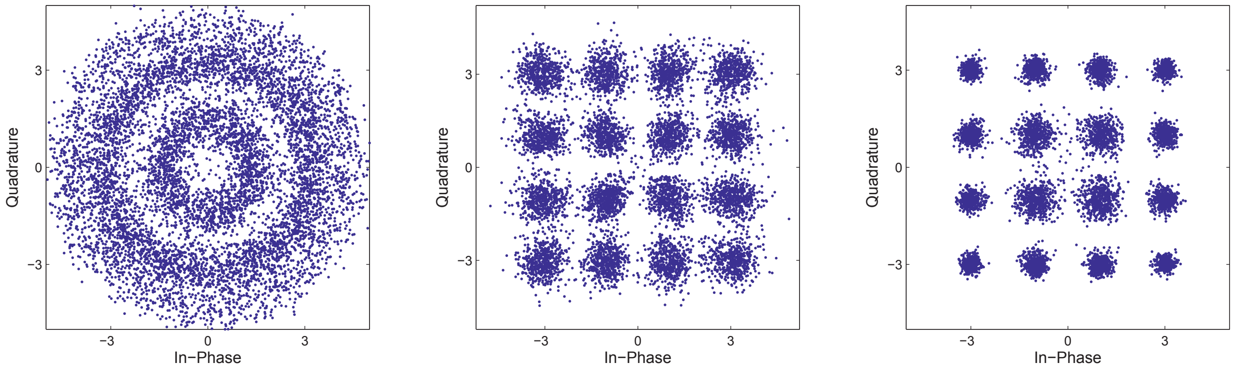

Figure 4 Constellation plot with FO of 1 GHz (Left); Constellation plot for LKF after FO compensation (middle); Constellation plot for EKF after FO compensation (Right)

The constellation plots before and after the FO compensation using LKF and EKF for an OSNR of 20 dB are depicted in Fig. 4. Since the residual FO compensation using EKF in the second stage has been modeled to estimate the complex symbols directly without any involvement of the argument function, it reinforces the estimates closer to the actual signal constellation points. Moreover, the closer cluster clouds of EKF compared to that of LKF also shows better capability of EKF in mitigating the amplitude noise along with the residual FO compensation.
In order to evaluate the performance of EKF and LKF for the joint tracking of FO and phase noise, the laser linewidth has been varied from 0 kHz to 1 MHz in addition to the FO of 1 GHz. In the first stage of FO estimation using LKF and EKF, 200 training data symbols have been considered. After compensating for coarse FO in the first stage, the signals are further processed by LKF and EKF in the second stage for the joint compensation of residual FO and phase noise. Figure 5 depicts the BER vs. OSNR curves of LKF and EKF in the presence of FO as well as phase noise. Both the LKF and EKF do not show notable penalty in the presence of phase noise corresponding a laser linewidth of up to 500 kHz in addition to FO of 1 GHz, compared to the

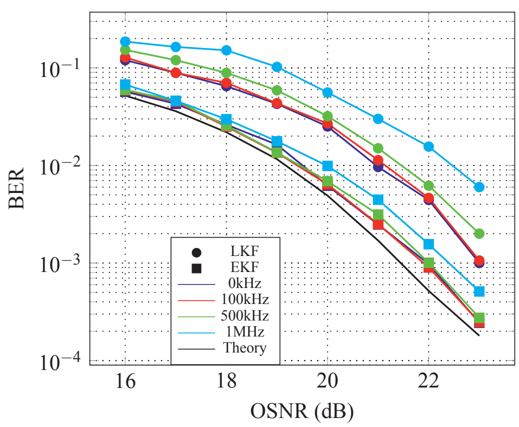

Figure 5 BER vs. OSNR curves for LKF and EKF after the residual FO and phase noise compensation for a FO of 1 GHz and varying laser linewidth.

curve with FO of 1 GHz and linewidth of 0 kHz. Taking the same reference curve with FO of 1 GHz and linewidth of 0 kHz, LKF shows a penalty of $\approx$ 1.5 dB at a BER of 2e-2, whereas, EKF shows only a penalty of $\approx$ 0.3 dB, when the laser linewidth has been increased to 1 MHz. By comparing the performance of LKF and EKF to the theory curve at a BER of 2e-2, LKF shows a penalty of $\approx$ 3 dB in the presence of FO of 1 GHz and linewidth of 1 MHz, whereas, EKF shows only a penalty of $\approx$ 0.6 dB. This manifests that the EKF has more tolerance towards the FO, phase noise as well as amplitude noise. However, EKF requires more complex multiplications compared to LKF to recover one symbol. Nevertheless, EKF does not require angle operations as contrary to LKF and is more immune to the additional phase errors.

4 Conclusions

We proposed a two stage extended Kalman filtering (EKF) method for the joint compensation of frequency offset (FO), phase and amplitude noise. In the first stage, a coarse FO estimate has been obtained from a set of training data symbols. In the second stage, another EKF based on CPANE algorithm has been employed for the residual FO compensation besides phase and amplitude noise. A similar two stage model based on linear Kalman filtering (LKF) has also been implemented for the joint tracking of FO and phase noise. Numerical results on 28 Gbaud polarization multiplexed (PM) 16-quadrature amplitude modulation (QAM) system manifests that the EKF outperforms LKF with greater tolerance towards FO, phase and amplitude noise.

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