Two Stage Extended Kalman Filtering for Joint Compensation of Frequency Offset, Linear and Nonlinear Phase Noise and Amplitude Noise in Coherent QAM Systems

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ABSTRACT

We investigate our proposed two stage extended Kalman filtering (EKF) technique for the joint tracking of frequency offset (FO), laser phase noise, fiber nonlinearity as well as amplitude noise. The EKF employed in the first stage coarsely compensates the FO using a set of training data symbols. In the second stage, the employed EKF accomplishes the task of compensating the residual FO, phase noise arising from laser linewidth, fiber nonlinear effects along with simultaneous amplitude noise mitigation. The transmission performance of the proposed two stage EKF has been verified through numerical simulations on polarization multiplexed (PM) 16-quadrature amplitude modulation (QAM) system operating at 28 Gbaud. The results prove that the proposed technique is well tolerant towards the impairments of FO, linear and nonlinear phase noise and amplitude noise even up to ≈3000 km of standard single mode fiber (SSMF) transmission at a launch power of 3 dBm, giving a bit error rate (BER) of ≈2.4e-2 which is the 20% soft decision forward error correction (SD-FEC) threshold. Furthermore, the proposed two stage EKF outperforms a similar two stage approach implemented using linear Kalman filter (LKF) with improved BER.

Keywords: Digital signal processing, nonlinear mitigation, frequency offset, extended Kalman filter, Phase noise, ASE noise.

1. INTRODUCTION

In order to meet the ever growing data traffic, the contemporary research is focused on developing 400 Gbps and above, Ethernet transmission [1]-[4]. Coherent detection with digital signal processing (DSP) has made it possible to deploy higher order modulation formats and multiplexing techniques which allow for efficient utilization of the bandwidth [5]-[6]. However, they are more susceptible to fiber transmission impairments as well as to the carrier phase and frequency offset (FO). Therefore, DSP algorithms for carrier synchronization and nonlinear mitigation are still under active research [7]-[16]. Recently, Kalman filtering has gained significant attention owing to its capability to mitigate several optical transmission impairments simultaneously. Extended Kalman filtering (EKF) is under wide investigation for joint mitigation of linear and nonlinear phase noise as well as amplitude noise [8]-[9], carrier phase/polarization tracking [17]-[19], and frequency offset estimation [10]-[11].

In [20], we proposed a two stage EKF for the joint tracking of laser phase noise, amplitude noise and the FO between the transmitter and local oscillator (LO) laser. In this work, we describe the algorithm in more detail and extend our two stage EKF model to compensate the effect of fiber nonlinearities in addition to the laser phase noise and FO. In the first stage, a coarse estimate of FO is obtained by an EKF which utilizes a set of training data symbols, and the signals are coarsely compensated for FO. In the second stage, we employ our proposed carrier phase and amplitude noise (CPANE) algorithm implemented using EKF to compensate the residual FO, laser phase noise, fiber nonlinearity as well as amplitude noise. The proposed technique has been verified through numerical simulations on a 28 Gbaud polarization multiplexed (PM) 16-quadrature amplitude modulation (16-QAM) system for different transmission distances over standard single mode fiber (SSMF). We further compare the performance of the two stage EKF to a similar two stage approach based on linear Kalman filtering (LKF). The numerical results justify that the proposed two stage EKF is well capable of mitigating the FO, laser linewidth effects as well as fiber nonlinearities simultaneously and outperforms the LKF method.

2. PRINCIPLES OF TWO STAGE EKF

Assuming perfect linear equalization, the input signal on single polarization, to the two stage EKF can be modeled as in equation (1). Here, $r(k)$ and $a(k)$ denote the complex received and transmitted symbols, respectively, at the k^{th} time instant. ω denotes the FO between the transmitter laser and LO, T_s denotes the symbol duration and $n(k)$ denotes the collective amplified spontaneous emission (ASE) noise. $\Phi(k) = \phi(k)^L + \phi(k)^{NL}$ denotes the total phase noise arising from the laser linewidth effects $\phi(k)^L$ and the fiber nonlinearity $\phi(k)^{NL}$.

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

In order to obtain the measurement for the FO, ω, the first step is to wipe off the data phase, which can be carried out using training data symbols. After normalizing the amplitude modulation, the FO measurement can

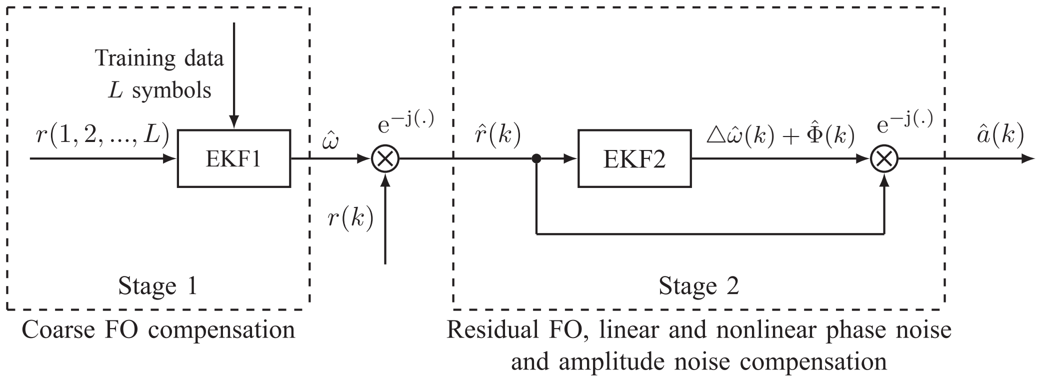

Figure 1: *Block diagram of the proposed two stage EKF algorithm*

be obtained by computing the phase difference between two adjacent symbols as described in [11], and is given in equation (2). Here, $m(k)$ denotes the measurement equation, $v(k) = \Phi(k) - \Phi(k-1)$ denotes the difference of the total phase noise between the two adjacent symbols, and $\eta(k)$ is the additive white Gaussian noise (AWGN). By taking the argument of equation (2), the FO measurement can also be obtained in the linear form as given in equation (3), where $\theta(k)$ denotes the linear FO measurement and $\xi(k)$ denotes AWGN. By considering the observation model in equation (2) for the EKF in the first stage, a coarse estimate of the FO, $\hat{\omega}$, can be obtained using a set of L training symbols. The signals after the first stage of coarse FO compensation can be represented as given in equation (4).

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

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

$$\hat{r}(k) = a(k)\mathrm{e}^{j(\triangle\omega(k) + \Phi(k))} + \alpha(k) \tag{4}$$

$$\psi(k) = \triangle\omega(k) + \Phi(k) + \beta(k) \tag{5}$$

Here, $\hat{r}(k)$ represents the received signal for the EKF, after the first stage of coarse FO compensation, $\triangle\omega(k)$ denotes the residual FO, and $\alpha(k)$ denotes AWGN. In the second stage, we employ our proposed CPANE algorithm using EKF for the joint tracking of residual FO, linear and nonlinear phase noise as well as amplitude noise. Since, the state estimate is modeled as a complex quantity in CPANE, it facilitates also for the mitigation of amplitude noise and further avoids the additional errors induced by the angle operations used typically for the LKF and also in carrier phase estimation. The block diagram illustrating the two stage EKF model is depicted in Fig. 1. The observation model for the second stage in case of LKF, for the joint tracking of residual FO, linear and nonlinear phase noise, can be obtained by taking the argument of equation (4) and is represented in equation (5). Here, $\psi(k)$ denotes the received signal for the LKF, after the first stage of coarse FO compensation and $\beta(k)$ denotes AWGN. In the second stage, both the LKF and EKF operate in the decision directed mode.

3. NUMERICAL MODEL AND RESULTS

The numerical performance of the two stage LKF and the two stage EKF has been verified on a PM-16-QAM system operating at 28 Gbaud. These signals at different launch powers are transmitted over a distance of 960 km (80 km x 12 spans) through SSMF with physical parameters of attenuation $\alpha = 0.2$ dB/km, dispersion $D = 17$ ps/nm-km, and nonlinear co-efficient $\gamma = 1.2$ /km-W. The per span power losses are compensated by an erbium doped fiber amplifier (EDFA) with a gain of 16 dB and a noise figure (NF) of 5 dB. For simplicity, we neglect the polarization mode dispersion (PMD) in this study. At the receive side, we employ a dual polarization coherent receiver with DSP module. The FO between the transmitter laser and LO has been set to 1 GHz and the laser phase noise has been set to 100 kHz. Firstly, the coherently detected signals are resampled to twice the symbol rate and are followed by the dispersion compensation. Later on, the signals are further re-sampled to the symbol rate and passed on to the two stage LKF/EKF. The simulation model used for the investigations is depicted in Fig. 2. In the first of EKF/LKF, 200 training data symbols were utilized to obtain a coarse FO estimate. The process and measurement noise covariances for the LKF/EKF in both the stages, have been set to optimize the performance. In stage 2, both LKF and EKF are operated in the decision directed mode, and the required decisions are obtained by de-rotating the received signal with an average of the past phase estimates as described in [9].

Figure 3(a) depicts the BER vs. launch power curves for the LKF and EKF after 960 km of SSMF transmission, with and without a FO of 1 GHz. Considering the case without the FO, at a launch power of 3 dBm, in the nonlinear regime, EKF shows slightly better performance compared to LKF. In the presence of FO of 1 GHz

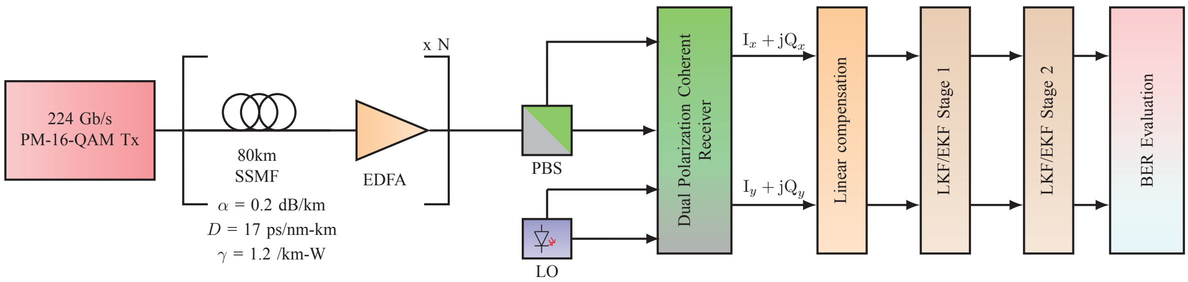

Figure 2: Simulation model of PM-16-QAM coherent transmission with DSP module

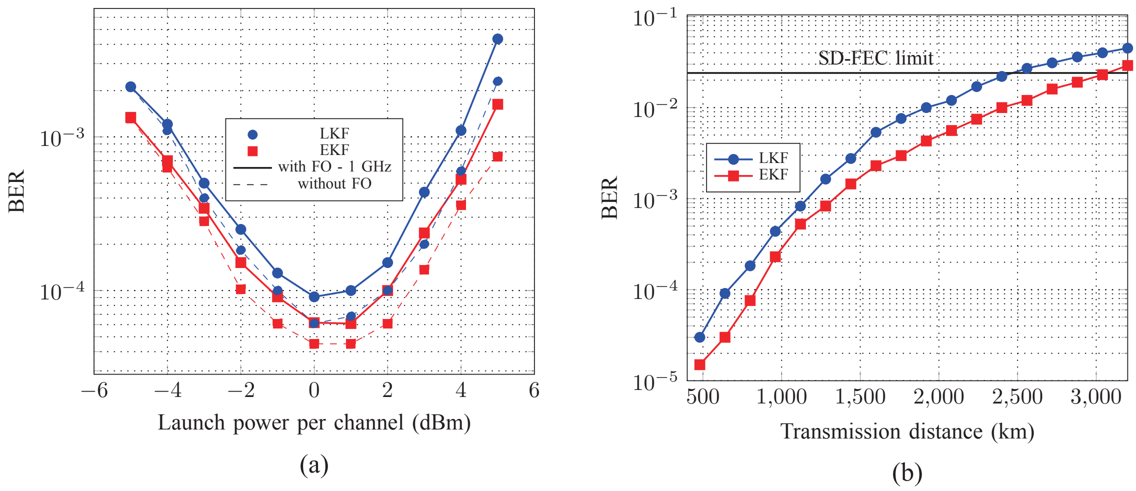

Figure 3: (a): *BER vs. launch power per channel for PM-16-QAM after 960 km of SSMF transmission with and without FO of 1GHz, and LO linewidth of 100 kHz*, (b): *BER vs. transmission distance for PM-16-QAM SSMF transmission at a launch power of 3 dBm, FO of 1 GHz and LO linewidth of 100 kHz*

in addition to the fiber nonlinearities, the performance of both LKF and EKF slightly degrades. However, EKF outperforms LKF by increasing the nonlinear system tolerance by $\approx$0.7 dB in the nonlinear regime, and exhibits a better tolerance towards FO, linear and nonlinear phase noise. This improved performance comes with slightly increased computational effort, as EKF requires a few additional complex multiplications compared to LKF. Nevertheless, EKF works directly on the constellation points and does not require any angle operations which would eliminate the additional errors induced and also non-linear functions like phase unwrapping as contrary to LKF. The BER as a function of transmission distance at a launch power of 3 dBm, FO of 1 GHz and LO linewidth of 100 kHz is depicted in Fig. 3(b). It can be observed that, the EKF outperforms LKF with an increased maximum possible transmission reach at the same BER. At a BER of 2.4e-2 which is the limit for soft decision forward error correction (SD-FEC) with an overhead of 20% [21], a transmission of up to $\approx$3000 km is possible with EKF, which is $\approx$500 km more than the possible transmission reach using LKF. The improved performance exhibited by EKF compared to LKF can be attributed to the fact that the EKF has been modeled to estimate the complex symbols directly without any involvement of the argument function, and also the observation model is more accurate compared to LKF. Therefore, EKF reinforces the estimates closer to the actual signal constellation points mitigating also the amplitude noise.

4. CONCLUSIONS

We proposed a two stage extended Kalman filtering (EKF) method for the joint compensation of frequency offset (FO), laser phase noise, fiber nonlinearities as well as amplitude noise. In the first stage, an EKF has been employed to obtain a coarse estimate of the FO using a set of training data symbols. After compensating the signals for coarse FO, the signals are further processed in the second stage. Here, another EKF has been employed based on the carrier phase and amplitude noise (CPANE) algorithm to compensate the residual FO, linear and non-linear phase noise and amplitude noise. A similar two stage approach based on linear Kalman filtering (LKF) has also been implemented. The performance of the afore-mentioned methods have been verified through numerical simulations on a polarization multiplexed (PM) 16 quadrature amplitude modulation (QAM) coherent systems operating at 28 Gbaud. The numerical results after 960 km of SSMF transmission prove that the EKF outperforms LKF with better tolerance towards FO, linear and non-linear phase noise. It has also been verified that with the two stage EKF, the maximum possible transmission reach at the same BER can be increased compared to the two stage LKF, and at a BER of 2.4e-2, EKF allows an additional 500 km of transmission compared to LKF. However, the EKF requires more computational effort compared to LKF and can be sought to be compensated by the angle operations required for the LKF.

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