# Kalman Filter Based Impairment Mitigation in Nonlinear Optical Systems with Equalization Enhanced Phase Noise


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***Abstract*—Kalman filter based estimation is developed to mitigate phase distortions in a DP-16QAM optical communication system with significant equalization enhanced phase noise. It outperforms the Viterbi-Viterbi approach by 1.84 dB.**



***Keywords—optical fiber communication, digital nonlinearity compensation, Kalman filter, laser phase noise, electronic dispersion compensation, equalization enhanced phase noise.***


## I. Introduction

Optical transmission impairments have been mitigated individually to ensure the sufficient signal quality to meet dramatic increase of demands on data capacity. However, the interaction between laser phase noise (LPN) and chromatic dispersion (CD), namely, equalization enhanced phase noise (EEPN) [1, 2] will severely degrade the performance of nonlinear optical fiber transmission systems, while it cannot be well compensated using digital signal processing. EEPN will become more significant in the transmission systems with the increment of symbol rate, transmission distance, modulation format [1]. These factors are critical in next-generation long-haul core optical telecommunication infrastructure to support the high-volume data traffic in 5G and beyond networks [3]. It has been reported that the estimator using Kalman filter (KF) can compensate for phase fluctuations effectively with a low computational complexity [4]. In this work, a KF is developed in a 32-GBd dual-polarization 16-*ary* quadrature amplitude modulation (DP-16QAM) nonlinear optical communication system over a standard single mode fiber (SSMF) to mitigate the LPN and the EEPN. It is shown that the KF outperforms Viterbi-Viterbi (VV) estimator [5] by 1.84 dB at peak signal-noise ratios (SNRs).

## II. Principle of Kalman Filter Based Estimator

Considering a 16-QAM nonlinear coherent system shown in Fig. 1, the $k^{th}$ received symbol $r_k$ to the estimator can be formulated as $r_k = s_k \mathrm{e}^{j\theta_k} + n_k$, where $s_k$ is the $k^{th}$ transmitted symbol from the modulator, $\theta_k$ involves the phase fluctuations generated by the fiber nonlinearity (FNL) [6], the LPN, the EEPN, the amplified spontaneous emission (ASE) noise, and the interaction between FNL and ASE noise [7], and $n_k$ includes the ASE noise, the EEPN, and the signal-EEPN interaction. KF is applied for the estimation of $\theta_k$ from the received symbol $r_k$. The state space model for the KF can be written as $\theta_k = \theta_{k-1} + w_k$, and $z_k = \arg\left(r_k t_k^*\right) = \theta_k + v_k$, where $w_k$ and $v_k$ are process and measurement noises, and their co-variances denoted by Q and R, respectively. $z_k$ is the measurement variable, and $t_k = decision(r_k e^{-j\hat{\theta}_{k|k-1}})$. The prediction procedure of the KF-based estimator includes $\hat{\theta}_{k|k-1} = \hat{\theta}_{k-1}$, and $P_{k|k-1} = P_{k-1} + Q$, where $P$ is the error covariance. The measurement update steps are $K_k = \dfrac{P_{k|k-1}}{P_{k|k-1} + R}$, $\hat{\theta}_k = \hat{\theta}_{k|k-1} + K_k\left(z_k - \hat{\theta}_{k|k-1}\right)$, and $P_k = \left(1 - K_k\right) \cdot P_{k|k-1}$. $K_k$ is the Kalman gain. The final symbols recovered by the KF-based estimator is given by $\hat{s}_k = r_k \mathrm{e}^{-j\hat{\theta}_k}$.

## III. . Transmission Setup

Numerical simulations have been carried out in a 32-GBd DP-16QAM optical communication system over a 2000 km SSMF with 80 km fiber at each span. The simulation setup is described in Fig.1. The transmitted symbol sequences are fully random and independent in two polarizations. The signal propagation over the fiber is simulated based on the split-step Fourier solution of the Manakov equation. The noise figure of EDFA is 4.5 dB. At the coherent receiver (Rx), the received signals are mixed with a local oscillator (LO) laser carrier (a 100 kHz linewidth). An electronic dispersion compensation (EDC) or a digital backward propagation (DBP) module is applied to compensate for CD or FNL. An ideal carrier phase estimation (CPE), a KF-based estimator and a VV


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CPE are applied, respectively, for the compensation of residual transmission distortions, e.g. LPN and EEPN. The laser frequency offset and the polarization mode dispersion (PMD) are neglected.

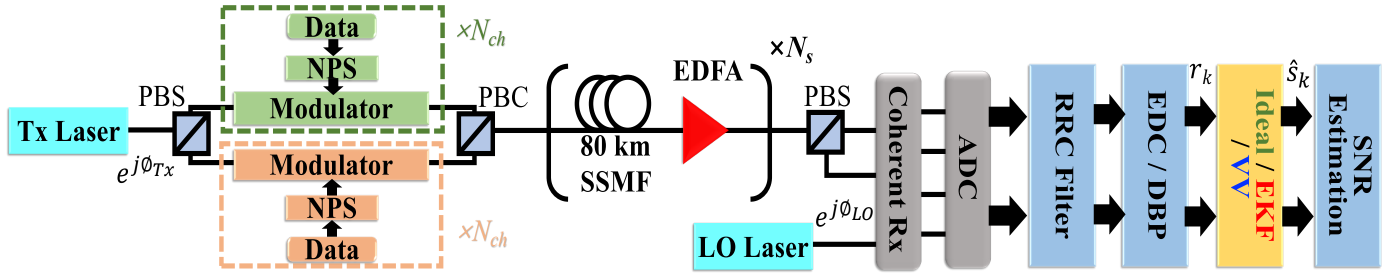


Fig. 1. DP-16QAM optical fiber transmission system. NPS: Nyquist pulse shaping; PBS: polarization beam splitter; PBC: polarization beam combiner; EDFA: erbium-doped fiber amplifier. ADC: analog-to-digital converter.

## IV. Results and Discussions

As described in Fig. 2, markers on the left side represent simulation results. It is observed that the system applied with the KF-based estimator achieves higher SNRs than the system using the ideal CPE in both cases of EDC and DBP. At the optimum power in the case of DBP (at 10 dBm), the peak SNR of KF is ~1.84 dB higher than that of the VV scheme. This indicates a strong capability of KF-based estimator in mitigating phase distortions. Their corresponding constellations at optimum launch powers are also shown on the right side. It can be found that the distortions in the KF scheme are smaller than those in the VV approach.

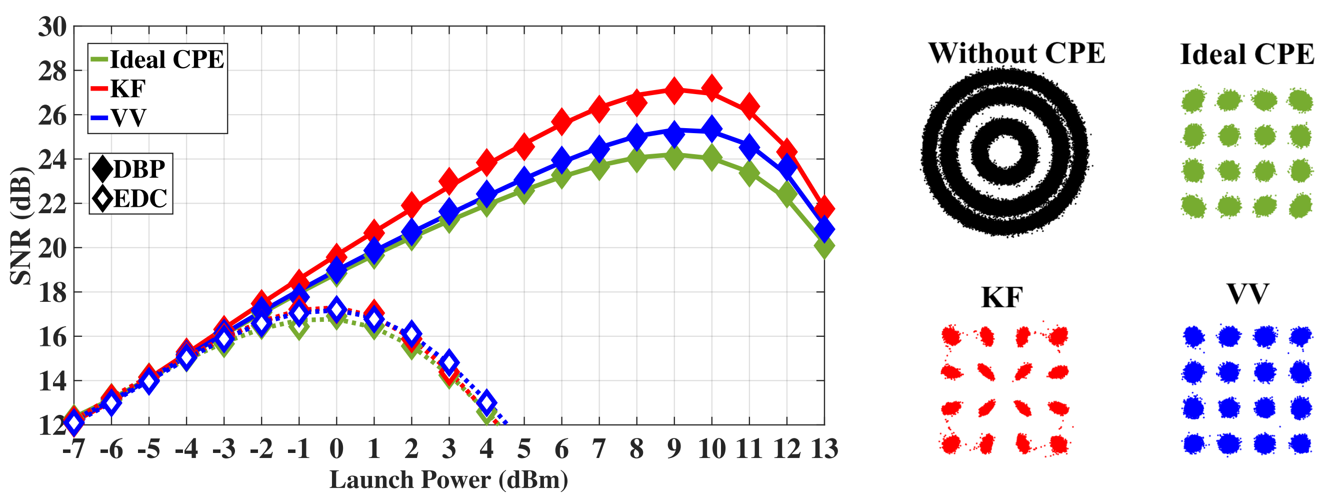


Fig. 2. SNR of a DP-16QAM optical system applied with ideal CPE, KF and VV estimators (left), and their constellations at optimum launch powers (right).

## References


[1] W. Shieh and K. Ho, "Equalization-enhanced phase noise for coherent-detection systems using electronic digital signal processing," Opt. Express, vol. 16, no. 20, pp. 15718–15727, September 2008.

[2] C. Jin, et al., "Nonlinear coherent optical systems in the presence of equalization enhanced phase noise," J. Lightw. Technol., vol. 39, no. 14, pp. 4646–4653, July 2021.

[3] "Cisco annual internet report (2018–2023) white paper," https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html#.

[4] A. Jain and P. K. Krishnamurthy, "Phase noise tracking and compensation in coherent optical systems using Kalman filter," IEEE Commun. Lett., vol. 20, no. 6, pp. 1072-1075, June 2016.

[5] A. J. Viterbi and A. M. Viterbi, "Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission," IEEE Trans. Inf. Theory, vol. 29, pp. 543–551, July 1983.

[6] E. Temprana, et al., "Overcoming Kerr-induced capacity limit in optical fiber transmission," Sci., vol. 348, no. 6242, pp. 1445–1448, June 2015.

[7] A. Ghazisaeidi, "A theory of nonlinear interactions between signal and amplified spontaneous emission noise in coherent wavelength division multiplexed systems," J. Lightw. Technol., vol. 35, no. 23, pp. 5150–517, December 2017.