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Experimental investigation of extended Kalman Filter combined with carrier phase recovery for 16-QAM system

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ABSTRACT

Performance of Extended Kalman Filter combined with the Viterbi–Viterbi phase estimation (VVPE-EKF) for joint phase noise mitigation and amplitude noise equalization is experimental demonstrated. Experimental results show that, for 11.2 Gbaud SP-16-QAM, the proposed VVPE-EKF achieves 0.9 dB required OSNR reduction at bit error ratio (BER) of 3.8e-3 compared to the VVPE. The result of maximum likelihood combined with VVPE (VVPE-ML) is only 0.3 dB. For 28 GBaud SP-16-QAM signal, VVPE-EKF achieves 3 dB required OSNR reduction at BER = 3.8e-3 (7% HD-FEC threshold) compared to VVPE. And VVPE-ML can reduce the required OSNR for 1.7 dB compared to the VVPE. VVPE-EKF outperforms DD-EKF 3.7 dB and 0.7 dB for 11.2 GBaud and 28 GBaud system, respectively.

1. Introduction

High-order modulation format such as 16 quadrature amplitude modulation (16-QAM) combined with coherent detection and digital signal processing (DSP) has provided a very significant meaning of increasing optical fiber transmission capacity and spectral efficiency [1]. Compared with quadrature phase shift keying (QPSK), 16-QAM signals are sensitive to phase noise (PN) and amplitude noise (AN). The PN is induced by the transmitter and local oscillator (LO) laser. And the main source of AN is amplified spontaneous emission (ASE) noise or the nonlinear interaction of ASE noise and the signal [1–4], as the constellation points are inherently closer in the Euclidean plane [2,3]. Various blind carrier phase recovery (CPR) algorithms have been proposed to compete the phase noise. Among them, the modified Viterbi–Viterbi phase estimator (VVPE) was recognized one of the most popular CPR methods [4], which is derived from the traditional VVPE based on quadrature phase shift keying (QPSK) partitioning approach. Later, the VVPE combined with blind linear equalization algorithm such as maximum likelihood (VVPE-ML) was recognized to enhance the linewidth tolerance of the VVPE [5,6]. However, the performances of these CPR are constrained by AN as well as the nonlinear induced interactions of the ASE noise and the signal [5,6]. Recently, machine learning techniques such as decision directed Extended Kalman Filter (DD-EKF) for adaptive equalization are reviewed and employed which compensate the impairment from observed data and build a probabilistic model of the impairment [7–10]. The DD-EKF demonstrated an optimal PN and AN tracking method in the minimum mean squared error (MMSE) sense in coherent QAM systems with lower laser linewidth [7]. However, DD-EKF cannot work well with higher laser linewidth [11]. Therefore, we report a joint laser PN and AN mitigation by combining modified VVPE with DD-EKF, named VVPE-EKF in [11], and numerically validated the VVPE-EKF method in the 25 GBaud 16-QAM coherent transmission system.

In this paper, we experimentally investigate the performances of VVPE, VVPE-ML and VVPE-EKF for 11.2 GBaud and 28 GBaud single polarization 16-QAM (SP-16-QAM) signals. The bit error rate (BER) performances are further evaluated with different VVPE block lengths, EKF noise variances and ML block lengths. With optimal parameters, for 11.2 GBaud 16-QAM, VVPE-EKF achieves 0.9 dB required OSNR reduction at BER = 3.8e−3 (7% HD-FEC threshold) over VVPE. The result of VVPE-ML is only 0.3 dB. For 28 GBaud signal, the required OSNR reduction of VVPE-EKF is 3 dB at BER = 3.8e−3 (7% HD-FEC threshold) compared to VVPE. And VVPE-ML can reduce the required OSNR for 1.7 dB compared to the VVPE. By combination with VVPE, VVPE-EKF outperforms DD-EKF 3.7 dB and 0.7 dB for 11.2 GBaud and 28 GBaud system, respectively. The paper is distributed as follows. In Section 2, the principle of the DD-EKF used in this paper and experimental setup are presented. Section 3 describes the optimal parameter and experimental results. Finally, conclusions are drawn in Section 4.

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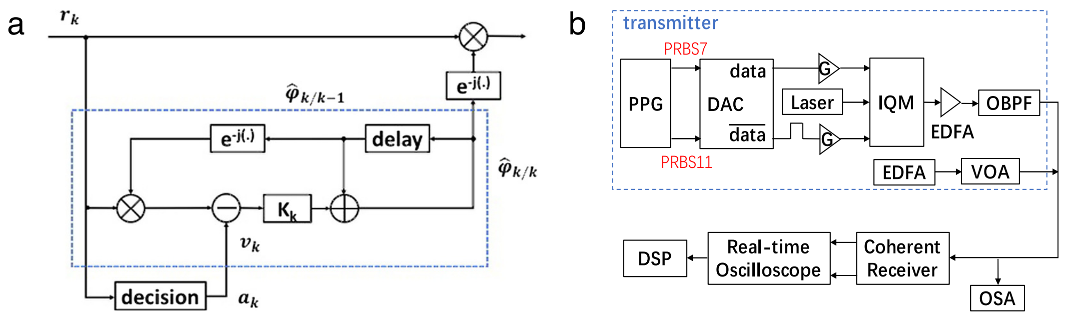

Fig. 1. (a) Block diagram of DD-EKF algorithm, (b) Experimental setup for 11.2 GBaud and 28 GBaud SP-16-QAM transmission system.

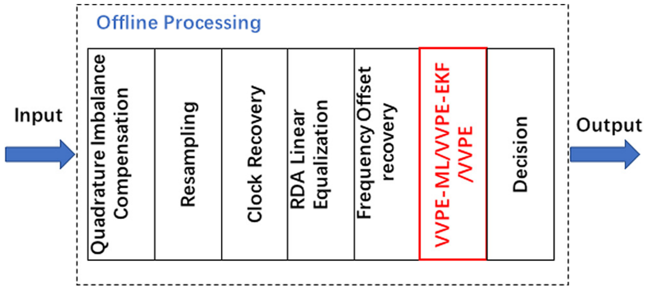

Fig. 2. Offline DSP processing.

2. Principle and experimental setup

2.1. Principle of the DD-EKF

Fig. 1(a) shows the block diagram of the DD-EKF. The received signals are represented as Eq. (1), where a_k is the decision signal. n_k models AN of the received signal.

$$r_k = a_k e^{j\theta_k} + n_k. \tag{1}$$

The state model of PN is given by

$$\theta_k = \theta_{k-1} + \omega_k. \tag{2}$$

The posterior estimation $\hat{\varphi}_k$ of DD-EKF is the optimal estimation of θ_k in the minimum mean square error sense. Equations of DD-EKF as follows:

Prediction stage:

$$\hat{\varphi}_k^- = \hat{\varphi}_{k-1}. \tag{3}$$

Correction stage:

$$\begin{aligned}
P_k^- &= P_{k-1} + Q_k \\
H_k &= \left.\frac{\partial\left(a_k e^{j\theta}\right)}{\partial\theta}\right|_{\theta=\hat{\varphi}_k^-} = j a_k e^{\hat{\varphi}_k^-} \\
K_k &= P_k^- K_k^* \left(H_k P_k^- H_k^* + R_k\right)^{-1} \\
P_k &= \left(1 - K_k H_k\right) P_k^- \\
\upsilon_k &= a_k - r_k e^{-j\hat{\varphi}_k^-} \\
\hat{\varphi}_k &= \hat{\varphi}_k^- + K_k \upsilon_k.
\end{aligned} \tag{4}$$

Where $\hat{\varphi}_k^-$ is the prior estimation at time instant k which is based on all the past estimations. P_k^- and P_k correspond to the error covariances of $\hat{\varphi}_k^-$ and $\hat{\varphi}_k$. Q_k and R_k are the covariances of process and measurement noise, respectively. υ_k is the difference between prediction and measurement. H_k is the linear transformation matrix. The prior estimation $\hat{\varphi}_k^-$ will be corrected by the innovation $\upsilon_k$weighted by the Kalman gain K_k. Since the innovation υ_k is calculated as a vector error and includes both phase and amplitude estimate errors. EKF is attractive to mitigate the accumulated AN and PN. The initial condition for $\hat{\varphi}_0$ is set to be 0 and P_0 to be 1. The performance of DD-EKF depends on Q_k and R_k which will be discussed in Section 3.1. Then r_k is derotated by $r_k e^{-j\hat{\varphi}_k}$.

Fig. 1(b) shows the experimental setup for 11.2 GBaud and 28 GBaud SP-16-QAM systems. The transmitter consists of a pulse pattern generator (PPG), a digital to analog converter (DAC), an optical IQ modulator (IQM). The PPG generates 2^7-1 and $2^{11}-1$ pseudo random bit sequences (PRBS) at 11.2 Gb/s or 28 Gb/s, the DAC combined the generated bit sequences to obtain four-level signals. The differential outputs of DAC are delayed by 5 bits and further being amplified by an electrical linear amplifier which are applied to an optical IQM. The input electrical signals are modulated onto a laser source with 100 kHz linewidth. The output 16-QAM signal is amplified by an Erbium-doped Optical Fiber Amplifier (EDFA) and filtered by an optical band-pass filter (OBPF) with a 3 dB bandwidth of 1.3 nm to enhance the signal

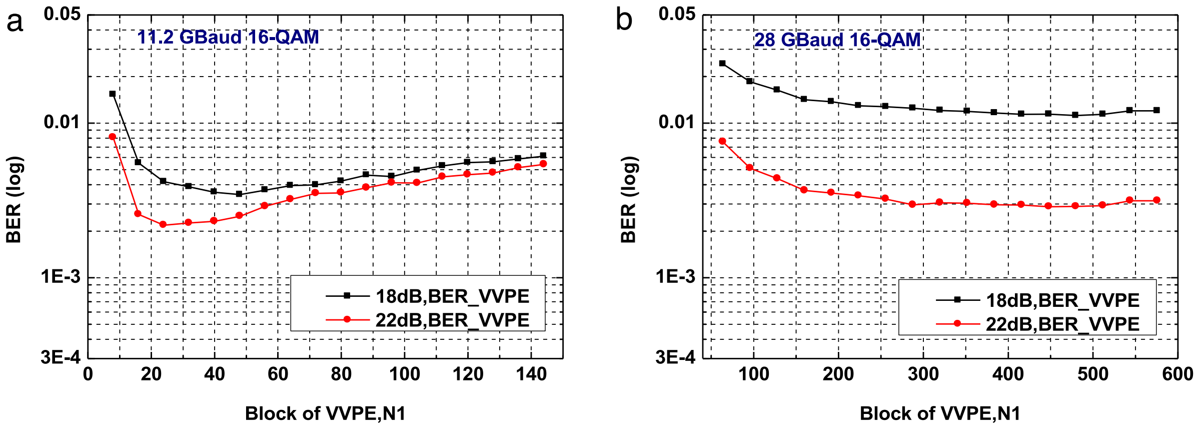

Fig. 3. (a) BER vs. variable block lengths of VVPE (N1) for 11.2 GBaud 16-QAM (OSNR = 18 dB, 22 dB), (b) BER vs. variable block lengths of VVPE (N1) for 28 GBaud 16-QAM (OSNR = 18 dB, 22 dB).

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