Effects of laser phase noise on the performance of optical coherent receivers*

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Laser phase noise (LPN) plays an important role in optical coherent systems. Based on the algorithm of Viterbi-Viterbi carrier phase estimation (CPE), the effects of LPN imposed on the coherent receivers are investigated for quadrature phase shift keying (QPSK), 8 phase shift keying (8PSK) and 16-quadrature amplitude modulation (16-QAM) optical coherent systems, respectively. The simulation results show that the optimal block length in the phase estimation algorithm is a tradeoff between LPN and additive white Gaussian noise (AWGN), and depends on the level of modulation formats. The resolution requirements of analog to digital converter (ADC) in the coherent receivers are independent of LPN or the level of modulation formats. For the bit error rate (BER) of 10^{-3}, the required bit number of ADC is 6, and the gain is marginal for the higher resolution.
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The combination of the high-level modulation format and coherent receiver is an important way to further increase the capacity of existing fiber infrastructures[1-4]. In coherent receivers, the carrier phase is required to demodulate the information which is modulated on the carrier. Therefore, laser phase noise (LPN), which causes the phase of carrier change randomly, plays an important role in coherent optical transmission systems[5]. The traditional method of demodulating coherent optical signals is to use an optical or electrical phase locked loop (PLL) that synchronizes the frequency and phase of the local oscillator (LO) with the transmitter laser[6]. Because PLLs are sensitive to propagation delay inside, coherent detection with a PLL has strict requirements on laser linewidth[7]. With fast digital signal processing (DSP) technology becoming available, the carrier phase estimation (CPE) algorithms are widely used for recovering the carrier in recently reported digital optical coherent receivers with LO running freely[8-13]. In this paper, to reveal negative effects of LPN on the performance of digital optical coherent receivers, the optimal block length and its range in CPE algorithm are analyzed for different modulation formats based on Viterbi-Viterbi phase estimation (VVPE) algorithm[14]. It shows that the optimal paramters of CPEs closely depend on modulation formats and their constellations. Otherwise, the resolution requirements on analog to digital converter (ADC) are almost independent of LPN or the levels of modulation formats for reaching the bit error rate (BER) of 10^{-3}.

The typical DSP-based optical coherent receiver is shown in Fig.1. The received signal $E_s(t)$ is superimposed with the LO signal $E_{LO}(t)$ in a 2×4 optical hybrid, whose outputs are detected by two balanced detectors. The photocurrents are converted into digital forms by high speed ADC, and then processed by the DSP module, including dispersion compensation, carrier phase estimation and decision.

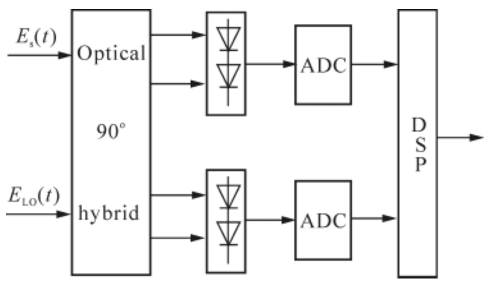

Fig.1 Schematic diagram of the typical DSP-based digital optical coherent receiver

The basic principle of carrier phase estimation used in this paper is shown in Fig.2. Assume that the input signal is $i(T_s)=e^{j[\theta(T_s)+\phi(T_s)]}$, where $\theta(T_s)$ and $\phi(T_s)$ denote modulated in-

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formation and carrier phase, respectively. The signal is separated into two branches firstly and then one branch goes through VVPE algorithm for estimating the carrier phase $\hat{\phi}(T_s)$. The stages of VVPE are as follows. In order to wipe off the modulated information, the input signal is raised to the Mth power, where M depends on the modulation formats and their levels, for quadrature phase shift keying (QPSK) and square 16-quadrature amplitude modulation (QAM), M=4, and for 8 phase shift keying (8PSK) and star 16-QAM, M=8. Additive white Gaussian noise (AWGN) is restrained by the average filter with the optimal block length in the next step. Finally, the phase estimation is obtained by calculating the argument of the filtered complex signals. If the phase error $|\phi(T_s)-\hat{\phi}(T_s)|$ is less than the given threshold, the correct demodulation $\hat{i}(T_s)$ could be obtained after decision.

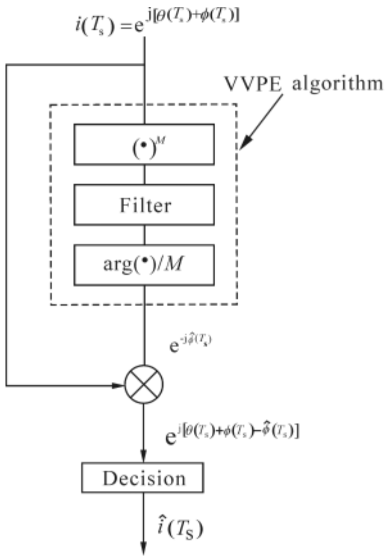


Fig.2 Principle of carrier phase estimation and VVPE algorithm used in this paper

The optimal block lengths are simulated for QPSK, 8PSK, square 16-QAM, and star 16-QAM (the ring ratio in the constellation is 1:1.8) with respect to LPN, respectively. Assume the fiber dispersion is completely compensated and there is no nonlinearities in transmission. The LPN is modeled as the Wiener process[15]. Within a symbol duration of $T_s=1/R_s$, the variance of phase change is given by $2ð\cdot\Delta v\cdot T_s$, where Äv represents the linewidth sum of the lasers at transmitter and receiver, and R_s is the symbol rate. In general, $\Delta v/R_s$ is used for denoting the relative value of LPN.

The simulation results are shown in Fig.3, where the legend <m,n> means that $\Delta v/R_s=m\times10^{-4}$, and the signal-to-noise ratio (SNR) penalty is n dB. It is noted that for any modulation format, SNR is increased to reach BER of 10^{-3} with LPN increasing. Because the step of SNR increasing is 0.05 dB in the simulations, the minimum BER for each curve is not ex-

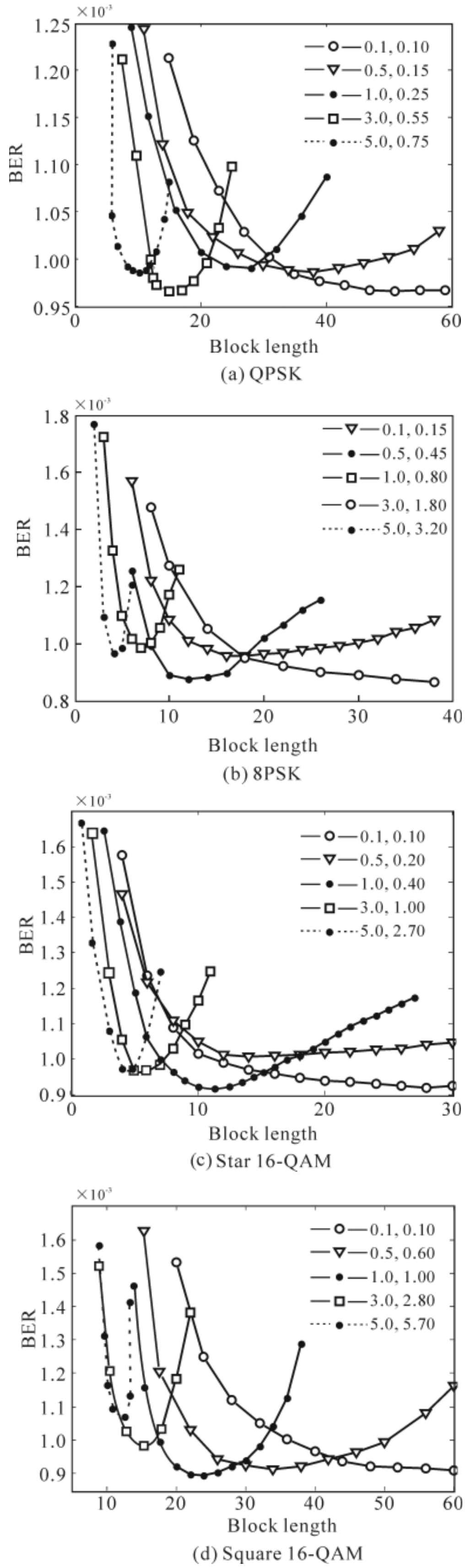
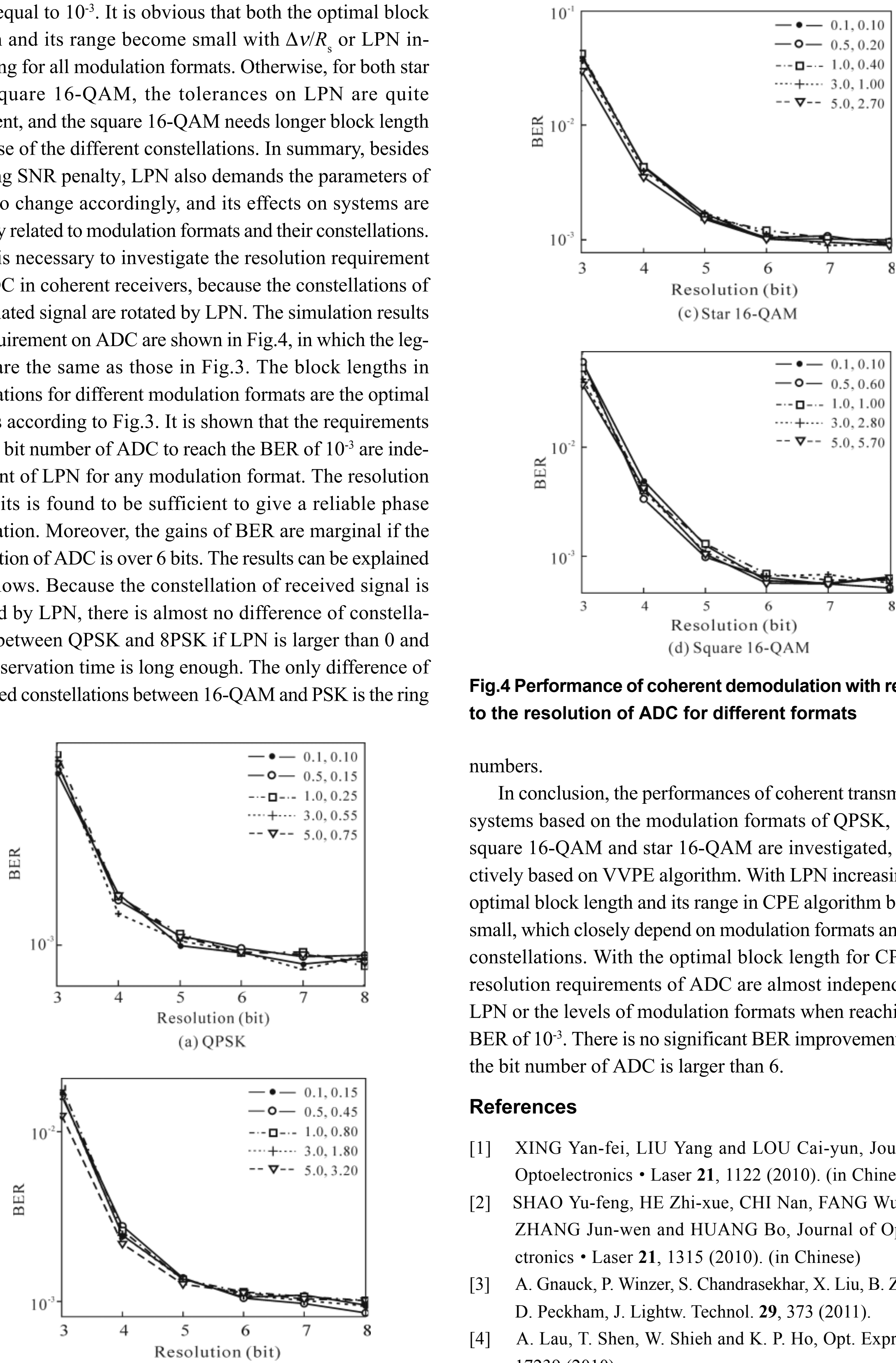


Fig.3 Simulation results of BER versus the optimal length of filters in VVPE with different $\Delta v/R_s$ values and SNR penalties

actly equal to 10^{-3}. It is obvious that both the optimal block length and its range become small with $\Delta v/R_s$ or LPN increasing for all modulation formats. Otherwise, for both star and square 16-QAM, the tolerances on LPN are quite different, and the square 16-QAM needs longer block length because of the different constellations. In summary, besides causing SNR penalty, LPN also demands the parameters of CPE to change accordingly, and its effects on systems are closely related to modulation formats and their constellations.

It is necessary to investigate the resolution requirement of ADC in coherent receivers, because the constellations of modulated signal are rotated by LPN. The simulation results of requirement on ADC are shown in Fig.4, in which the legends are the same as those in Fig.3. The block lengths in simulations for different modulation formats are the optimal values according to Fig.3. It is shown that the requirements on the bit number of ADC to reach the BER of 10^{-3} are independent of LPN for any modulation format. The resolution of 6 bits is found to be sufficient to give a reliable phase estimation. Moreover, the gains of BER are marginal if the resolution of ADC is over 6 bits. The results can be explained as follows. Because the constellation of received signal is rotated by LPN, there is almost no difference of constellations between QPSK and 8PSK if LPN is larger than 0 and the observation time is long enough. The only difference of received constellations between 16-QAM and PSK is the ring numbers.



(a) QPSK

(b) 8PSK

(c) Star 16-QAM

(d) Square 16-QAM

Fig.4 Performance of coherent demodulation with respect to the resolution of ADC for different formats

In conclusion, the performances of coherent transmission systems based on the modulation formats of QPSK, 8PSK, square 16-QAM and star 16-QAM are investigated, respectively based on VVPE algorithm. With LPN increasing, the optimal block length and its range in CPE algorithm become small, which closely depend on modulation formats and their constellations. With the optimal block length for CPE, the resolution requirements of ADC are almost independent of LPN or the levels of modulation formats when reaching the BER of 10^{-3}. There is no significant BER improvement when the bit number of ADC is larger than 6.

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