Impact of local oscillator frequency noise on coherent optical systems with electronic dispersion compensation

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Abstract: A theoretical investigation of the equalization-enhanced phase noise (EEPN) and its mitigation is presented. We show with a frequency domain analysis that the EEPN results from the non-linear inter-mixing between the sidebands of the dispersed signal and the noise sidebands of the local oscillator. It is further shown and validated with system simulations that the transmission penalty is mainly due to the slow optical frequency fluctuations of the local oscillator. Hence, elimination of the frequency noise below a certain cut-off frequency significantly reduces the transmission penalty, even when frequency noise would otherwise cause an error floor. The required cut-off frequency increases linearly with the white frequency noise level and hence the linewidth of the local oscillator laser, but is virtually independent of the symbol rate and the accumulated dispersion.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications.

References and links

1. E. Ip, A. P. T. Lau, D. J. F. Barros, and J. M. Kahn, "Coherent detection in optical fiber systems," Opt. Express **16**(2), 753–791 (2008).
2. R. Saunders, M. Traverso, T. Schmidt, and C. Malouin, "Economics of 100 Gb/s transport," in *Proc. of OFC* (San Diego, California, 2010), paper. NMB.2.
3. I. Garrett and G. Jacobsen, "Phase noise in weakly coherent systems," IEE Proceedings J. Optoelectronics, **136**(3), 159–165 (1989).
4. N. G. Gonzalez, A. C. Jambrina, R. Borkowski, V. Arlunno, T. T. Pham, R. Rodes, X. Zhang, M. B. Othman, K. Prince, X. Yu, J. B. Jensen, D. Zibar, and I. T. Monroy, "Reconfigurable digital coherent receiver for metro-access network supporting mixed modulation formats and bit-rates," in *Proc. of OFC* (Los Angeles, California, 2011), Paper. OMW.7.
5. W. Shieh and K. P. Ho, "Equalization-enhanced phase noise for coherent-detection systems using electronic digital signal processing," Opt. Express **16**(20), 15718–15727 (2008).
6. M. Iglesias Olmedo, X. Pang, M. Piels, R. Schatz, G. Jacobsen, S. Popov, I. Tafur Monroy, and D. Zibar, "Carrier Recovery Techniques for Semiconductor Laser Frequency Noise for 28 Gbd DP-16QAM," *Proc. of OFC* (Los Angeles, California, 2015), paper Th2A.10.
7. A. P. T. Lau, T. S. R. Shen, W. Shieh, and K. P. Ho, "Equalization-enhanced phase noise for 100 Gb/s transmission and beyond with coherent detection," Opt. Express **18**(16), 17239–17251 (2010).
8. T. Xu, G. Jacobsen, S. Popov, J. Li, A. T. Friberg, and Y. Zhang, "Analytical estimation of phase noise influence in coherent transmission system with digital dispersion equalization," Opt. Express **19**(8), 7756–7768 (2011).
9. G. Jacobsen, M. S. Lidón, T. Xu, S. Popov, A. T. Friberg, and Y. Zhang, "Influence of pre- and post compensation of chromatic dispersion on equalization enhanced phase noise in coherent multilevel systems," J. Opt. Commun. **32**, 257–261 (2012).
10. G. Jacobsen, T. Xu, S. Popov, and S. Sergeyev, "Study of EEPN mitigation using modified RF pilot and Viterbi-Viterbi based phase noise compensation," Opt. Express **21**(10), 12351–12362 (2013).
11. G. Jacobsen, T. Xu, S. Popov, J. Li, A. T. Friberg, and Y. Zhang, "EEPN and CD study for coherent optical nPSK and nQAM systems with RF pilot based phase noise compensation," Opt. Express **20**(8), 8862–8870 (2012).
12. R. Farhoudi, A. Ghazisaeidi, and L. A. Rusch, "Performance of carrier phase recovery for electronically dispersion compensated coherent systems," Opt. Express **20**(24), 26568–26582 (2012).

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13. Q. Zhuge, X. Xu, Z. A. El-Sahn, M. E. Mousa-Pasandi, M. Morsy-Osman, M. Chagnon, M. Qiu, and D. V. Plant, "Experimental investigation of the equalization-enhanced phase noise in long haul 56 Gbaud DP-QPSK systems," Opt. Express **20**(13), 13841–13846 (2012).
14. S. Oda, C. Ohshima, T. Tanaka, T. Tanimura, H. Nakashima, N. Koizumi, T. Hoshida, H. Zhang, Z. Tao, and J. Rasmussen, " Interplay between local oscillator phase noise and electrical chromatic dispersion compensation in digital coherent transmission system," in *Proc. of ECOC* (Torino, Italy, 2010), Paper. Mo.1.C.2.
15. C. Xie, "Local oscillator phase noise induced penalties in optical coherent detection systems using electronic chromatic dispersion compensation," in *Proc.of OFC* (San Diego, California, 2009), Paper. OMT.4.
16. I. Fatadin and S. J. Savory, "Impact of phase to amplitude noise conversion in coherent optical systems with digital dispersion compensation," Opt. Express **18**(15), 16273–16278 (2010).
17. M. Ohtsu and S. Kotajima, "Linewidth reduction of a semiconductor laser by electrical feedback," IEEE J. Quantum Electron. **21**(12), 1905–1912 (1985).
18. G. Colavolpe, T. Foggi, E. Forestieri, and M. Secondini, "Impact of phase noise and compensation techniques in coherent optical systems," J. Lightwave Technol. **29**(18), 2790–2800 (2011).
19. www.vpiphotonics.com.
20. R. Kudo, T. Kobayashi, K. Ishihara, Y. Takatori, A. Sano, and Y. Miyamoto, "Coherent Optical Single Carrier Transmission Using Overlap Frequency Domain Equalization for Long-Haul Optical Systems," J. Lightwave Technol. **27**(16), 3721–3728 (2009).

1. Introduction

Coherent detection together with digital signal processing offers a promising solution in terms of receiver sensitivity, dispersion resilience, and particularly the phase noise tolerance [1–3]. In addition, it also possesses desirable features that meet the critical requirement of future-generation reconfigurable networks [4]. However, in coherent optical systems with electronic dispersion compensation (EDC), it is observed that the received constellation, even after digital signal processing, remains influenced by enhanced noise commonly known as equalization-enhanced phase noise (EEPN) originating from the phase noise of the local oscillator (LO) [5]. Although conventional semiconductor lasers with Lorentzian linewidths in 1-10 MHz range can be used as transmitter lasers in coherent systems with suitable phase recovery algorithms [6], EEPN normally excludes them from being used as LO lasers. Instead, one has to resort to more costly and less compact external cavity lasers. W. Shieh et al. provided the theoretical evaluation of EEPN based on the enhancement of the local oscillator (LO) phase noise due to the dispersion equalization [5,7]. An analytical estimation of bit error rate (BER) for systems influenced with EEPN was provided by G. Jacobsen et al. in [8]. A detailed study on the impact of various chromatic dispersion (CD) compensation techniques and carrier phase estimation methods on EEPN was provided in [9–12]. Furthermore, EEPN in coherent optical systems with EDC was experimentally demonstrated in [12,13]. The previous studies have consistently concluded that EEPN penalty increases with accumulated dispersion and symbol rate, placing stringent requirement on linewidth of the LO, when using higher order quadrature modulation formats [5,7–16]. In this paper, we significantly expand this research topic emphasizing the impact of different spectral parts of laser frequency noise on the transmission penalty due to this enhanced noise.

In order to understand the influence of LO frequency noise on this enhanced noise we perform a frequency domain analysis of a coherent optical system with electronic dispersion compensation. The laser emission perturbed by Wiener phase noise described with a stochastic frequency response is used in this analysis. The findings of the frequency domain analysis are then validated through system simulations using quadrature phase shift keying (QPSK) and 16-quadrature amplitude modulation (QAM) for different symbol rates, accumulated dispersion and LO linewidths. The results of the paper indicate how EEPN can be effectively mitigated, thereby enabling the use of conventional semiconductor lasers with a Lorentzian linewidth up to 10 MHz as LO lasers in these systems.

2. Frequency domain analysis of coherent optical system with EDC

In this section, without loss of generality, we perform a frequency domain analysis of a coherent optical system with EDC. The baseband-equivalent frequency domain model is illustrated in Fig. 1. $R(f)$ is the baseband-equivalent stochastic spectrum after the

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modulation on the laser (including the influence of transmitter laser phase noise, sampling, pulse shaping filter etc.).

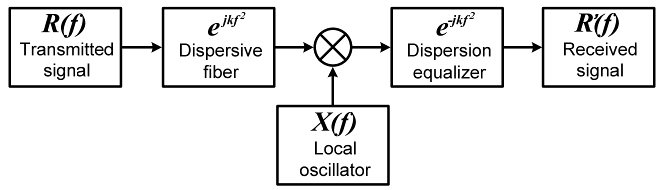

Fig. 1. Baseband-equivalent frequency domain model of a coherent optical system. The sources are represented with their stochastic Fourier transforms and the components with their transfer functions.

The received signal right after the dispersion compensation, $R'(f)$ in Fig. 1 is given as,

$$R'(f) = \left[R(f) \cdot e^{jkf^2} \otimes X(f) \right] \cdot e^{-jkf^2} \tag{1}$$

where e^{jkf^2} represents the frequency response of the all-pass dispersive channel with accumulated dispersion factor $k = \frac{\pi \cdot D \cdot l \cdot c}{f_0^2}$ where, D is the dispersion coefficient, l is the fiber length, c is the speed of light, f_0 is the central optical frequency and $X(f)$ represents the stochastic, baseband-equivalent Fourier Transform of the laser output influenced with frequency noise. It is important to note that multiplication and convolution possess non-associative property with respect to each other. Therefore, performing the operations in Eq. (1) in the order of their physical occurrence and taking e^{jkf^2} out of integral we get,

$$R'(f) = e^{jkf^2} \cdot \left[\int_{-\infty}^{\infty} R(f - f_1) \cdot e^{jk\left(f_1^2 + 2ff_1\right)} \cdot X(f_1)\, df_1 \right] \cdot e^{-jkf^2} \tag{2}$$

As we can see in Eq. (2), the first term represents the accumulated dispersion and the last term represents the frequency response of the linear channel equalizer. The middle term represents the inter-mixing of the side bands of the dispersed signal with the noise side bands of the local oscillator. Thus, the frequency domain analysis reveals that the linear part of the accumulated channel dispersion is compensated by the linear channel equalizer. However, the inter-mixing of side bands of the two signals in the intensity sensitive photo-detectors is not compensated in the linear equalizer, which results in an enhancement of noise.

Equation (2) can further be rearranged to separate the signal term and EEPN noise term as follows,

$$R'(f) = R(f) \cdot X(0) + \int_{-\infty, f_1 \neq 0}^{\infty} R(f - f_1) \cdot e^{jk\left(f_1^2 + 2ff_1\right)} \cdot X(f_1)\, df_1 \tag{3}$$

It can be seen that each frequency of the incoming signal is distorted by the enhanced noise, given by second part of Eq. (3).

The frequency noise of a laser can be attributed to perturbations of the phase of the optical field due to the spontaneous emission. In semiconductor lasers, the frequency noise is further enhanced, since also intensity fluctuations will, via stimulated recombination, induce noise in the carrier density that affects the refractive index and hence lasing frequency. If we neglect the internal laser dynamics, the frequency noise will be white, proportional to the spontaneous emission, yielding a Lorentzian linewidth. Representing the spontaneous emission noise with a stochastic baseband-equivalent Fourier transform, $\hat{e}_{sp}(f)$, the stochastic baseband-equivalent Fourier transform of the output of the LO laser will be

$$X(f)=\frac{\hat{e}_{sp}(f)}{j(2\pi f)+\frac{\Delta\gamma}{2}} \tag{4}$$

where $\Delta\gamma$ represent the angular Lorentzian linewidth. Inserting $X(f)$ in Eq. (2) we get,

$$R'(f)\approx\int_{-f_{cutoff}}^{f_{cutoff}} R(f-f_1)\cdot e^{jk\left(f_1^2+2ff_1\right)}\cdot\left(\frac{\hat{e}_{sp}(f_1)}{j(2\pi f_1)+\frac{\Delta\gamma}{2}}\right)df_1 \tag{5}$$

As we can see in Eq. (5), the influence of nearby signal frequencies on a given frequency is weighted by a deterministic factor $\left(j(2\pi f_1)+\frac{\Delta\gamma}{2}\right)^{-1}$. As long as both the symbol rate and the integration limit, f_{cutoff}, are sufficiently larger than the linewidth, the contribution to EEPN is governed by the above factor. The integration limit, f_{cutoff}, in Eq. (5), can then be defined as the frequency beyond which the contribution to EEPN from the spontaneous emission, $\hat{e}_{sp}(f)$ - and hence LO frequency noise - becomes negligible, based on a certain criterion. Conversely, by suppressing the frequency noise for frequencies below f_{cutoff}, we can mitigate most of the EEPN. From above discussion one can also conclude that f_{cutoff}, is determined by the LO linewidth and is virtually independent of symbol rate and accumulated dispersion. The necessary suppression of low frequency noise can be implemented by e.g., electrical feedback [17] or digital coherence enhancement [18]. The first method using electrical feedback will also reduce the measured FWHM (full width half maximum) linewidth of the local oscillator laser. Our results show that such a linewidth reduction can be efficient to mitigate EEPN even if the electrical feedback loop has a bandwidth much lower than the bandwidth of the transmitted signal.

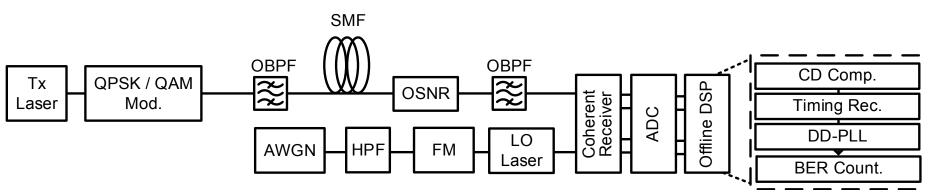

Fig. 2. Simulation setup. OBPF: Optical Band-Pass Filter, OSNR: noise loading, AWGN: Additive White Gaussian Noise generator, HPF: High-Pass Filter, FM: Frequency Modulator, ADC: Analog to Digital Converter, DD-PLL: Decision-Directed Phase-Locked-Loop.

3. Simulation results and discussion

In this section, we perform system simulations to support the analysis presented in Section 2. The simulations were performed in VPItransmissionMaker^{TM} [19] for transmission of 28 Gbaud and 56 Gbaud QPSK and 16-QAM modulation formats over a single mode fiber (SMF) link having CD coefficient of 16 ps/(nm·km), see Fig. 2. Data stream was generated using 2^{15}-1 pseudorandom bit sequence modulated on the optical carrier using Mach-Zehnder based in-phase and quadrature phase modulator. The incoming optical signal was loaded before reception with amplified spontaneous emission noise represented by the OSNR block. This emulates erbium-doped fiber amplifier noise that incrementally adds on to the signal after each fiber span. A frequency domain equalizer was used for dispersion compensation [20]. The LO influenced by white frequency noise was emulated by frequency modulation

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(FM) of an ideal LO laser with high-pass-filtered (HPF) additive Gaussian white noise source (AWGN). The lower cut-off frequency of the rectangular high-pass filter corresponds to the f_{cutoff} in Eq. (5). Decision-directed phase-locked-loop (DD-PLL) was used for carrier phase estimation.

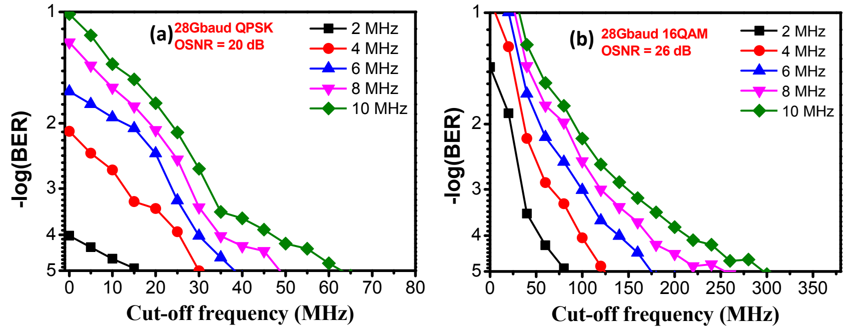

Fig. 3. BER vs. Cut-off frequency for 160 000 ps/nm accumulated dispersion and different LO linewidths. (a) QPSK, (b) 16-QAM.

In Fig. 3, the dependence of BER on the cut-off frequency of the high-pass filter for different LO linewidths, is presented. Over 1 000 000 bits and 160 000 ps/nm accumulated dispersion were taken into account for the obtained results. As expected, one can see a decrease in BER with increasing cut-off frequency since an increased part of noise is eliminated. However, the required cut-off frequency to achieve an acceptable BER is much lower than the symbol rate but increases with LO linewidth, as also indicated by the theoretical analysis in Section 2.

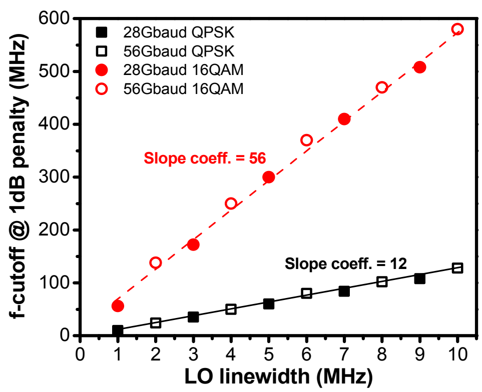

Fig. 4. Cut-off frequency for 1 dB OSNR penalty at BER = 10^{-3} vs LO linewidth for QPSK and 16-QAM.

The required f_{cutoff} to achieve overall optical signal to noise ratio (OSNR) penalty of 1 dB at BER of 10^{-3} is shown in Fig. 4 as a function of linewidth. It can be observed that the cut-off frequency scales linearly with the LO linewidth caused by white frequency noise. The required cut-off frequency f_{cutoff} depends on the affordable OSNR penalty and on the modulation format. The required cut-off frequency is 12 × linewidth for QPSK and 56 × linewidth for 16-QAM. We also see that the required cut-off frequency is virtually independent of the symbol rate as long as the required f_{cutoff} is sufficiently larger than the linewidth as concluded in Section 2.

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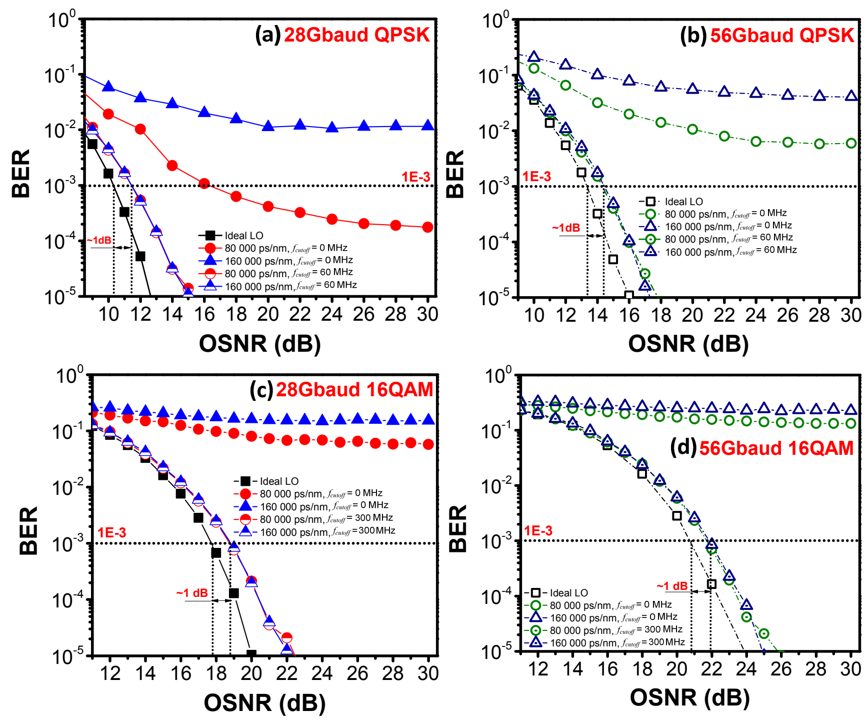

Fig. 5. BER vs. OSNR curves with and without filtering of low frequency noise of 5 MHz linewidth LO compared to ideal LO with accumulated dispersion shown in the inset. (a,b) QPSK, (c,d) 16-QAM.

Figure 5 depicts the BER vs. OSNR curves with and without high-pass filtering of frequency noise of an LO with 5 MHz linewidth. The filter cut-off frequency is determined from Fig. 4 to give a penalty less than 1 dB. The results are also compared to an ideal LO. It can be observed that, without high-pass filtering, the penalty increases with both symbol rate and accumulated dispersion for a given Lorentzian linewidth. However, the high-pass filtering of frequency noise reduces the penalty, as expected, to less than 1 dB, virtually independent of the symbol rate and the accumulated dispersion. Again it is concluded that, for a given modulation format, the cut-off frequency is only dependent on the LO linewidth. The necessary suppression of low frequency noise can be implemented by e.g., electrical feedback [17] or digital coherence enhancement [18] as mentioned in Section 2.

4. Conclusion

Frequency domain analysis identifies non-linear inter-mixing in the photodiode of sidebands of dispersed modulated signal with LO sidebands, as the origin of the enhanced noise. Furthermore, it is found that the EEPN penalty is mainly caused by the low frequency noise of the LO and can hence be mitigated by elimination of the frequency noise below a certain cut-off frequency. The required cut-off frequency for a given BER penalty and modulation format increases linearly with the LO linewidth, but is virtually independent of the symbol rate and the accumulated dispersion. Elimination of the frequency noise below this cut-off frequency, using e.g. frequency noise feedback to the LO laser or digital coherence enhancement, will significantly reduce the EEPN penalty even when it otherwise would cause an error floor.

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