The Impact of Nonlinear Phase Noise Induced from Low-speed Optical Supervisory Channel on Soft-Decision FEC Performance

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Abstract: We numerically analyze the statistics of the nonlinear phase noise induced from a low-speed optical supervisory channel wavelength-multiplexed outside the EDFA amplification band and how it affects the behavior and performance of soft-decision FEC.

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1. Introduction

Optical supervisory channel (OSC) plays an important role in wavelength-division-multiplexed (WDM) transmission systems for remote optical node management, monitoring and control. The OSC co-propagates with the 1550-nm band client signal-carrying wavelengths, outside the EDFA amplification band (typically at 1510 nm); it is terminated at intermediate amplifier sites. The OSC usually uses low-cost small form-factor pluggable modules that output optical signal is on-off-keying (OOK) modulated optical signals at the bitrate (155 Mb/s for OC-3 structure), i.e. much lower than that of the main signal (beyond 100 Gb/s).

We recently observed that the OSC imposed nonlinear phase noise on a polarization-division-multiplexed quadrature phase shift keying (PDM-QPSK) signal, and thus severely degraded the performance of soft-decision forward error correction (SD-FEC), even though the OSC wavelength was far from the WDM signal band [1]. However, the cause of such degradation has not been well explained; how the optical parameters related to the OSC signal contribute to SD-FEC performance degradation has not be explored.

In this study, we numerically analyze the statistics of OSC-induced phase noise on a PDM-QPSK signal and how it affects the behavior and performance of low-density parity-check (LDPC) code iterative decoding using density evolution [2]. The analysis indicates that the low bitrate OSC signal efficiently triggered nonlinear phase noise, despite the large walk-off parameter between the OSC and main signal. Furthermore, we show by density evolution analysis that the non-additive white gaussian noise (non-AWGN) nature of such phase noise significantly deteriorates LDPC decoding performance depending on the power and bitrate of the OSC signal, as well as the walk-off parameter.

2. Simulation model

The simulation setup is shown in Fig. 1(a). The transmitter encodes a pseudo random bit sequence (PRBS) of $2^{15}-1$ length using a rate-0.75 (300, 1200) regular LDPC code. The coded bits were used to generate a 32-Gbaud Nyquist (roll-off factor = 0.1) PDM-QPSK signal (λ_{sig} = 1528.77 - 1566.72 nm). The generated signal was injected with input power of -2 dBm into a 600-km fiber link consisting of twelve 50-km spans of non-zero dispersion shifted fiber (NZ-DSF) with a dispersion coefficient of 4.2 ps/nm/km and dispersion slope coefficient of 0.089 ps/nm^2/km at 1550 nm. An OSC signal (λ_{osc} = 1510 nm) was wavelength-multiplexed with the main signal at the input end of each span, and demultiplexed by an optical bandpass filter (OBPF) at an output end. To study the randomness of OSC-induced phase noise, the OSC signals for each span were polarization-scrambled before multiplexing, and uncorrelated time shifts (uniformly distributed) were added. Output power P_{osc} of the OOK-modulated OSC signal was varied to replicate a realistic power range in an commercial equipment, i.e. up to approximately 5 dBm, and bitrate R_{osc} was also varied, although a bitrate of 155 Mb/s is typically used. In addition, we examined the dependency of the OSC-induced phase noise on the walk-off parameter between the OSC and main signal, by setting different wavelengths of the main signal λ_{sig}. Figure 1(b) plots walk-off parameter as a function of the wavelength difference $\Delta\lambda = \lambda_{sig} - \lambda_{osc}$. After twelve spans of transmission and loading ASE light for adjusting a received optical signal-to-noise ratio (OSNR), the optical signal was detected by a coherent receiver. The baseband signal was passed through a digital signal processing (DSP) stage that offered static dispersion compensation, adaptive equalization, and carrier phase recovery (CPR). The average symbol length for CPR was set to 256 to better observe the phase noise. The log-likelihood ratio (LLR) was computed for each symbol, and then LDPC decoding with max iteration of 12 was performed. The post-FEC bit-error rate (BER) of the above model averaged over 30 trials was calculated as a function of the OSNR.

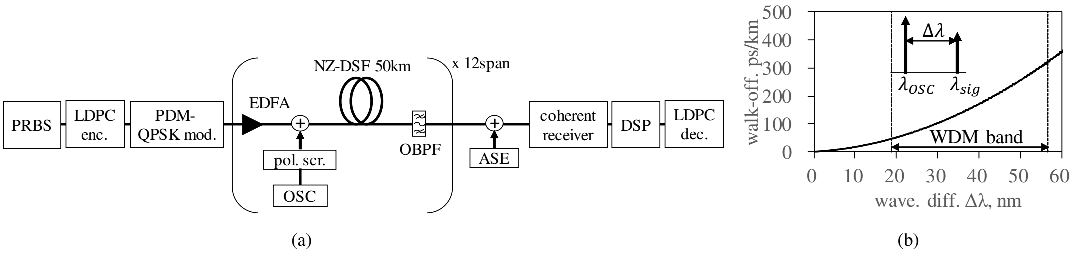


Fig. 1: Simulation model. (a) simulation setup and (b) inter-channel walk-off between OSC and main signal.

3. Statistics on OSC-induced phase noise

The power spectra of OSC-induced phase noise depends on both R_{osc} and λ_{sig} shown in Fig. 2(a). The phase noise was defined as the phase difference between the received symbols without and with the OSC signal (P_{osc} = 4 dBm). No ASE light was loaded to better observe the noise statistics. When R_{osc} decreased, the low-frequency component of spectral density was enhanced since the bandwidth of the OSC signal was reduced, as explained in the low-pass filter model of cross-phase modulation (XPM) [3], resulting in a non-flat spectrum. Moreover, when the walk-off parameter was reduced due to the shorter λ_{sig}, the high-frequency component was emphasized since the cut-off frequency increases in the above low-pass filter model, and thus, the phase noise power increased. Note that the low-frequency component of the obtained spectra was attenuated due to averaging of the phase noise in CPR. Therefore, the low-speed OSC signal effectively causes a strong non-AWGN phase noise on the shorter signal wavelengths within the WDM band.

For a more detailed analysis, we calculated the auto-correlations of the above phase noise as shown in Fig. 2(b). This results shows that a significant correlation between two symbols occurs over large time delays at low values of R_{osc} and short λ_{sig}, indicating that the such phase noise has strong non-AWGN nature. Additionally, Fig. 2(c) illustrates a constellation and probability density functions (PDFs) of the received signal with an OSNR of 25 dB at R_{osc} = 125 Mb/s, λ_{sig} = 1528.77 nm, and P_{osc} = 4 dBm. The PDFs were obtained by calculating along the u- and v- axes as defined in the constellation. Also plotted in the figure by solid lines are Gaussian fittings for the two axes. The PDF on the u-axes coincided with Gaussian fittings. On the other hand, the PDF on the v-axis increasingly deviated from Gaussian fittings. This indicates that the main signal superimposed with non-AWGN phase noise impacts SD-FEC, resulting in degraded SD-FEC performance as predicted in [4].

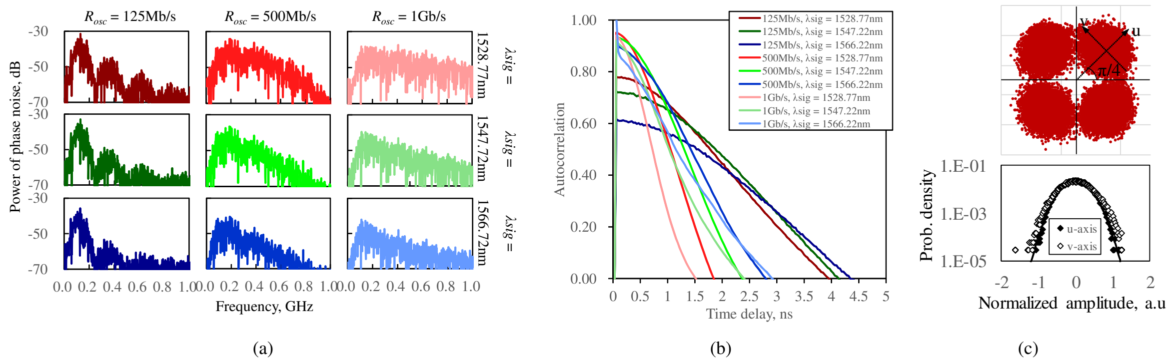
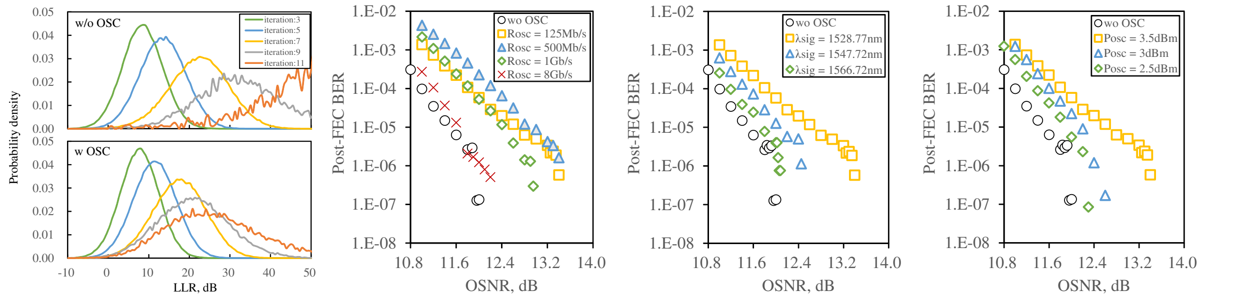


Fig. 2: Statistical property of OSC-induced phase noise. (a) dependency of the phase noise power spectra on the OSC signal bitrate and main signal wavelength, (b) auto-correlation of phase noise, and (c) signal constellation and probability density function of noise.

4. Behavior and performance of LDPC decoding

We used density evolution to investigate how the above OSC-induced phase noise affects the behavior of SD-FEC [2]. Density evolution observes the PDF of LLR messages exchaneged in LDPC decoding to determine the



(a) (b) (c) (d)

Fig. 3: Behavior and performance of LDPC decoding. (a) probability density function of LLR messages without and with OSC signal, and dependence of the post-FEC BER on (b) OSC signal bitrate, (c) main signal wavelength, and (d) OSC signal power.

maximum noise power that permits error-free transmission; it depends on the degree distribution of the target code. In this paper, we only examined the impact on the PDF due to the OSC-induced phase noise for a specific (300, 1200) regular LDPC code. Figure 3(a) illustrates PDFs of LLR messages for different number of iterations in LDPC decoding, without and with the OSC signal at R_{osc} = 125 Mb/s, λ_{sig} = 1528.77nm, and P_{osc} = 3.8 dBm, and the received OSNR of 12.4 dB. Without the OSC signal, the mean LLR in the PDF evolves rapidly in a positive direction as the number of iterations increases, and thus, the fraction of negative LLR messages approaches zero after a sufficient number of iterations. On the other hand, the evolution of the mean LLR was asymptotically limited with the OSC signal, and thus, a fraction of negative LLR messages remains even after sufficiently many iterations. Therefore, the OSC-induced phase noise degrades the noise threshold, and thus, a required OSNR increases for the identical post-FEC BER.

Figure 3(b), (c), and (d) plot post-FEC BER as a function of the OSNR, with parameters of R_{osc}, λ_{sig}, and P_{osc}, respectively. The OSNR penalty was defined as the difference from the OSNR without the OSC signal at a post-FEC BER $= 10^{-6}$. The OSNR penalties were 1.4 dB, 1.4 dB, 0.9 dB, and 0.2dB for R_{osc} = 125 Mb/s, 500 Mb/s, 1 Gb/s, 8 Gb/s, respectively, at λ_{sig} = 1528.77 nm and P_{osc} = 3.5 dBm, as shown in Fig. 3(b). The penalties were 0.2 dB, 0.4 dB, 1.4 dB for λ_{sig} = 1566.72, 1547.72, and 1528.77 nm, respectively, at R_{osc} = 125 Mb/s and P_{osc} = 3.5 dBm, as shown in Fig. 3(c). They were 0.1 dB, 0.5 dB, 1.4 dB for P_{osc} = 2.5 dBm, 3 dBm and 3.5 dBm, respectively, at R_{osc} = 125 Mb/s and λ_{sig} = 1528.77 nm, as shown in Fig. 3(d). This results supports the above characterization on the statistics of OSC-induced phase noise and the behavior of LDPC decoding.

5. Conclusion

We numerically analyzed the statistics of the nonlinear phase noise induced from an optical supervisory channel and investigated soft-decision FEC performance in presence of such phase noise. We obtained insights that the low-speed OSC signal efficiently causes strong non-AWGN phase noise, even though the OSC wavelength is far from the WDM signal band; this noise significantly degrades the performance of soft-decision FEC depending on the bitrate and power of the OSC signal, and a client-signal carrying wavelength. These insights indicate that it is necessary to pay attention to the above optical parameters related to the OSC signal in optical transmission design, and a countermeasure such as a power adjustment of the OSC signal may be required.

References

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