High-Speed Long-Haul Multi-Channel Nonlinear Optical Communication Systems Influenced by Equalization Enhanced Phase Noise

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***Abstract*—In this work, the performance of high-speed long-haul nonlinear Nyquist-spaced multi-channel coherent optical fiber communication systems utilizing electronic dispersion compensation and digital nonlinearity compensation is explored taking into consideration the enhanced equalization phase noise. The analytical model has also been developed to estimate the system performance under different transmission scenarios.**

Keywords*—optical fiber communication, analytical model, laser phase noise, electronic dispersion compensation, equalization enhanced phase noise

I. INTRODUCTION

Nowadays, demands on transmission data rate have been growing dramatically. A Nyquist-spaced high-speed long-haul transmission has been implemented to enhance the information capacity, which requires strict limitation on the optical signal distortions. Some of these distortions, such as chromatic dispersion (CD), fiber nonlinear interference (NLI) [1], and laser phase noise (LPN) can be fairly well-mitigated by digital signal processing (DSP) techniques [2], [3]. However, some of these distortions, such as the equalization enhanced phase noise (EEPN), which occurs due to the net dispersion of transmitter (Tx) and local oscillator (LO) LPN [4], [5], can be difficult to compensate. Particularly, in dispersion unmanaged systems, the LO LPN can be severely dispersed by the CD compensation module [6]. Moreover, EEPN effect may also arise due to the interaction between fiber dispersion and Tx LPN [5], [7]. The amount of EEPN commonly scales with accumulated fiber chromatic dispersion, signal symbol rate, laser source linewidth, transmission bandwidth, as well as signal modulation format. Eventually, the EEPN effect may give rise to significant distortions of the transmitted signal in high-speed long-haul nonlinear systems.

In this paper, a 32-GHz and 64-GHz dual-polarization 16-*ary* quadrature amplitude modulation (DP-16QAM) 5-channel 2000 km Nyquist-spaced nonlinear optical transmission system was simulated considering the impact of EEPN effect. In this work, a more common scenario of the examined EEPN effect was considered, in which the EEPN was assumed to be induced by the LO LPN, rather than induced by Tx LPN. The analytical model based on the Gaussian noise (GN) model [8]–[12] has been introduced to predict the system performance considering two possible situations: the electronic dispersion compensation (EDC) and digital nonlinearity compensation (NLC) modules.

II. ANALYTICAL MODEL

Considering a nonlinear Nyquist-spaced multi-channel system in the presence of the EEPN effect, where the EDC module is applied, the effective signal-to-noise ratio (SNR) can be expressed as follows [12]–[14]

$$\mathrm{SNR}_{\mathrm{EDC}} = \frac{P}{P_{\mathrm{ASE}} + P_{\mathrm{NLI}} + \sigma^2_{\mathrm{EEPN}} \cdot P}, \tag{1}$$

where P represents the optical launch power per channel, P_{ASE} is the power of the ASE noise generated by the erbium-doped optical fiber amplifiers (EDFAs), P_{NLI} denotes the nonlinear signal interference power due to the optical Kerr effect [15], σ^2_{EEPN} is the total variance of EEPN [16]. The expressions of P_{ASE}, P_{NLI}, and σ^2_{EEPN} are, respectively, given by

$$P_{\mathrm{ASE}} = N\left(G-1\right)F_n hf_0 \cdot R, \tag{2}$$

$$P_{\mathrm{NLI}} = \eta\left(N, N_{\mathrm{ch}}\right) \cdot P^3, \tag{3}$$

$$\sigma^2_{\mathrm{EEPN}} = N\frac{\pi c D L f_{3\mathrm{dB}}}{2 f_0^2} \cdot R, \tag{4}$$

where N is the number of fiber spans in a link, G is the EDFA gain, F_n is the EDFA noise figure, h is the Planck constant, f_0 is the laser center frequency, R is the signal symbol rate, $\eta(N,N_{\mathrm{ch}})$ is the NLI distortion coefficient, N_{ch} is the total number of wavelength division multiplexing (WDM) channels, c is the light speed in vacuum, D is the chromatic dispersion coefficient, L is the fiber span length, and f_{3dB} denotes the 3-dB laser Lorentzian linewidth.

The NLC scenario leads to the following model:

$$\mathrm{SNR}_{\mathrm{NLC}} = \frac{P}{P_{\mathrm{ASE}} + P_{\text{Signal-ASE}} + \sigma^2_{\mathrm{EEPN}} \cdot P + P_{\text{Signal-EEPN}}}, \tag{5}$$

where $P_{\text{Signal-ASE}}$ and $P_{\text{Signal-EEPN}}$ stand for the signal-ASE and the signals and signal-EEPN interactions, respectively. These are caused by the four-wave mixing process when the optical signals experience the NLC module [12]. It should be noted that in the case of EDC, the influence of $P_{\text{Signal-ASE}}$ is much smaller than P_{NLI} term, and thus, can be omitted. When the full-field NLC is applied, the signal-signal NLI P_{NLI} can be entirely undone. In this case, the impact of signal-ASE interaction effect becomes comparatively significant and needs to be considered. The impact of $P_{\text{Signal-ASE}}$ and $P_{\text{Signal-EEPN}}$ can be evaluated as follows

$$P_{\text{Signal-ASE}} = 3\xi\eta(1,N_{\mathrm{ch}})P_{\mathrm{ASE}} \cdot P^2, \tag{6}$$

$$P_{\text{Signal-EEPN}} = 3\xi\eta(1,N_{\mathrm{ch}})(\sigma^2_{\mathrm{EEPN}} / N) \cdot P^3, \tag{7}$$

where $\eta(1,N_{\mathrm{ch}})$ denotes the NLI coefficient estimated over one fiber span, and the factor $\xi \triangleq \sum_{k=1}^{N} k^{\varepsilon+1}$ [8], [9] with ε being the coherence factor [14].

III. TRANSMISSION SYSTEMS

In order to explore the role of EEPN effect in high-speed long-haul nonlinear optical fiber systems, a Nyquist-spaced DP-16QAM WDM optical transmission system has been numerically simulated. The detailed schematic of simulation system setup is depicted in Fig. 1. A laser comb is applied as the Tx laser source. The symbol sequences in WDM channels are set to be random and independent. The Nyquist pulse shaping (NPS) is operated by a 0.1% roll-off root-raised cosine (RRC) filter. Standard single mode fiber (SSMF) is employed into a link, in which the optical signals propagation is modelled based on the split-step Fourier transform solution of the Manakov equation [17][18]. The total transmission distance is 2000 km with the fiber span length of 80 km. EDFAs are used for compensating the optical signal attenuation.

TABLE I. SYSTEM PARAMETERS

Parameters	Values	Units
Center wavelength	1550	nm
Attenuation coefficient	0.2	dB/km
CD coefficient	17	ps/nm/km
Nonlinear coefficient	1.2	1/W/km
EDFA noise figure	4.5	dB
Total fiber length	25×80	km
Number of channels	5	-
Modulation format	DP-16QAM	-
Roll-off factor	0.1	%

At the receiver, coherent detection is performed using the LO laser with a linewidth of 0 Hz and 100 kHz. Balanced photodetectors are employed for signal detection. The transmitted signals are sampled by analog-to-digital converters (ADCs). An RRC filter is employed for bandwidth selection before EDC or NLC process. The EDC module is operated by a frequency domain equalizer (FDE) [19]. The NLC is employed based on the reverse split-step Fourier transform method [20].

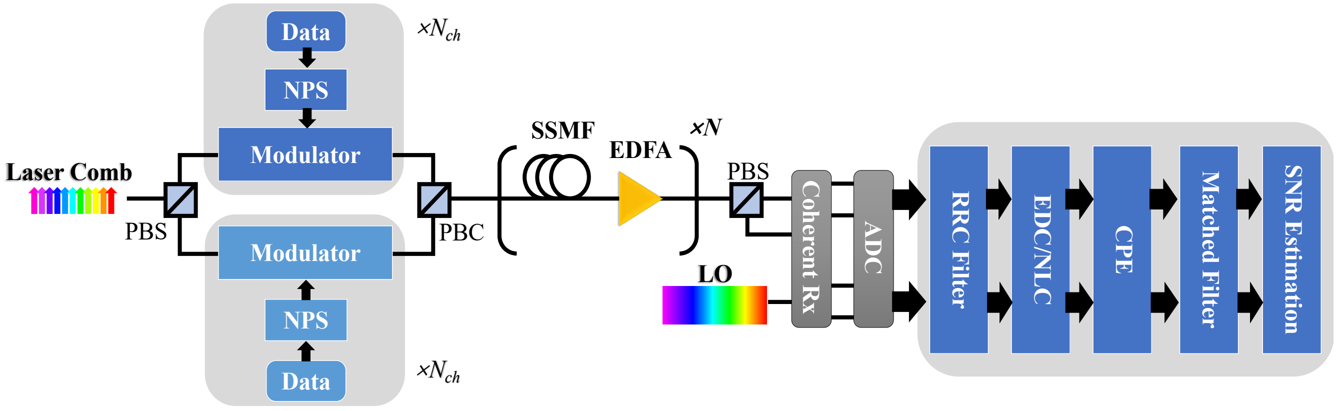

Fig. 1. Schematic of DP-16QAM Nyquist-spaced multi-channel nonlinear optical communication systems using EDC or NLC. NPS: Nyquist pulse shaping; PBS: polarization beam splitter; PBC: polarization beam combiner.

The phase noise due to LO laser is fully suppressed by means of the ideal carrier phase estimation (CPE) algorithm [5]. The matched filter is chosen to be a 0.1 % roll-off factor RRC filter for the observed channel selection. Finally, the signal-to-noise ratio (SNR) is used as the main system performance figure of merit. The effect of polarization mode dispersion (PMD) as well as the laser frequency offset are neglected in this work. The parameter values of the examined system are shown in Table I.

IV. RESULTS AND DISCUSSIONS

Results of simulation and analytical model for the 32-GHz 5-channel DP-16QAM 2000-km Nyquist-spaced nonlinear optical transmission system are shown in Fig. 2 [12]. Solid lines represent the analytical model predictions, whereas the markers are numerical simulation outputs. It is found that the SNR values obtained by the numerical simulations are in a good agreement with the analytical model predictions for both EDC and NLC scenarios. Significant performance impairments due to the presence of the EEPN effect are observed. When NLC is applied, the SNR can be reduced up to 1.41 dB due to the influence of EEPN effect at the optimal power regime. It is also shown that the noise due to EEPN slightly degrades system performance even in the case of EDC. However, it has much smaller impact in comparison with applied NLC case. This ascertains that the variance of EEPN in the case of EDC remains considerably larger than the $P_{\text{Signal-ASE}}$ term, whilst it still remains smaller than the P_{NLI} noise contribution.

Fig. 3 illustrates the results obtained for the 64-GHz DP-16QAM 5-channel 2000 km Nyquist-spaced transmission system performance. Excellent agreement between the simulation results and the analytical model estimation has also been achieved. It is shown that due to the EEPN effect, the decrease of SNR at the optimal power (about 10 dBm per channel) is observed to be from 23.7 dB to 21.4 dB. This SNR decrement is larger compared to the 32-GHz system, since the strength of EEPN effect is proportional to the transmission symbol rates. This clearly indicates the role and importance of the EEPN effect in particular for modern high-speed optical communication systems

Additionally, the LPN tolerance for high-speed long-haul nonlinear optical coherent transmission was also examined. Analytically estimated SNR values are converted to BERs [21]. Detailed transmission parameters used for prediction are show in Table I. Fig. 4 shows the analytical BER as a function of LO laser linewidth in the 64-GHz 5-channel Nyquist-spaced 2000-km system with the employed NLC. QPSK, 16QAM, and 64QAM modulation formats are considered. The dotted line represents the 4.5×10^{-3} BER threshold. In order to ensure the quality of received symbols, some requirements on the LO laser linewidth were theoretically explicated. In particular, the LO laser linewidths are upper-bounded by 1.00 MHz and 0.14 MHz for the DP-16QAM and DP-64QAM systems, respectively. However, within the LO laser linewidths frequency range from 0 to 5 MHz, all values of BER in the QPSK systems remain below the FEC threshold.

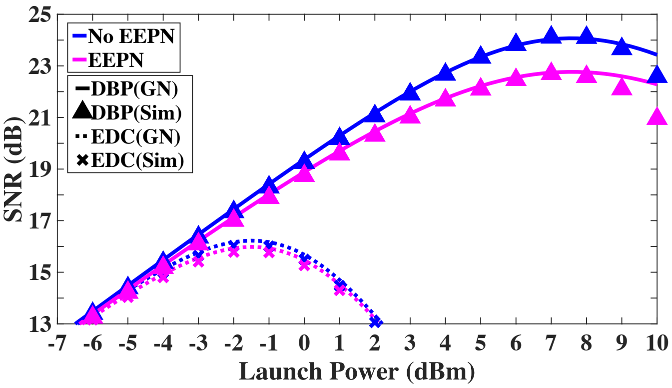

Fig. 2. The SNR of the central channel as a function of launch power per channel in the 32-GHz DP-16QAM 5-channel 2000 km Nyquist-spaced nonlinear optical transmission system.

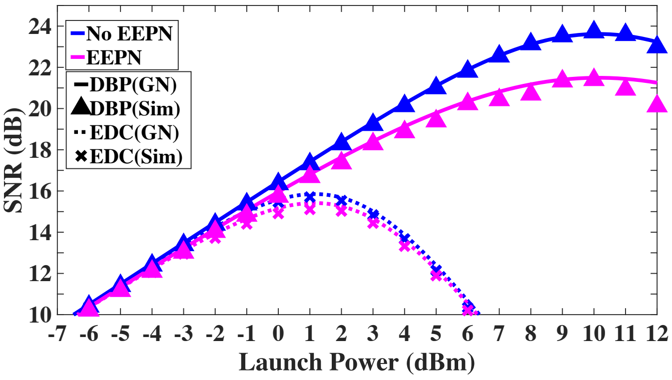

Fig. 3. The SNR of the central channel as a function of launch power per channel in the 64-GHz DP-16QAM 5-channel 2000-km Nyquist-spaced nonlinear optical transmission system.

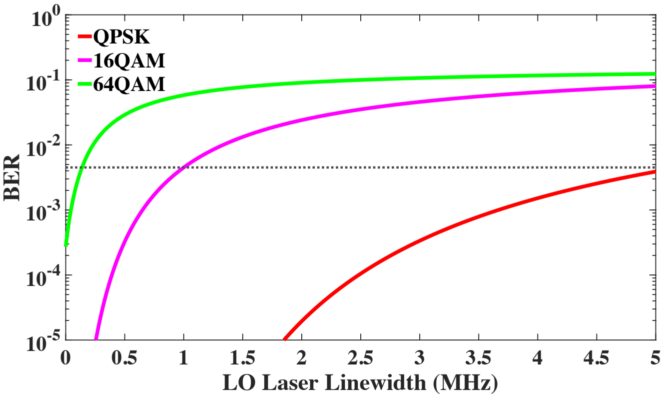

Fig. 4. The analytical BER as a function of LO laser linewidth in the 64-GHz 5-channel 2000-km Nyquist-spaced system using NLC for the modulation format of QPSK, 16QAM, and 64QAM.

V. CONCLUSION

In this work, the significance of EEPN contribution in high-speed long-haul nonlinear optical communication systems has been thoroughly examined. The accuracy of the analytical predictions considering the impact of EEPN has been verified. Simulation based results indicate the growth of EEPN impact with increasing either the LO laser linewidth or the symbol rate. This work demonstrates the importance of taken the effect of

EEPN into account, especially in a design of high-speed long-haul nonlinear optical transmission systems accounting for the non-zero values of laser linewidths.

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