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Study of Equalization Enhanced Phase Noise in EDFA-Amplified Optical Communication Systems

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Abstract— **The significant influence of equalization enhanced phase noise on the performance of long-haul EDFA-amplified optical fiber communication systems has been investigated in this paper. A 128-Gbaud DP-16QAM multi-channel 2400 km Nyquist-spaced optical transmission system has been considered, with the application of the electronic dispersion compensation and the digital nonlinearity compensation schemes.**

Keywords— **Optical fiber communication; Equalization enhanced phase noise; Analytical mode**

I. Introduction

The increasing demand for the data capacity poses high requirements on the quality of signals transmitted in fibers and the suppression of transmission impairments [1]–[4]. However, the interaction between the chromatic dispersion (CD) and the laser phase noise (LPN), also called equalization enhanced phase noise (EEPN) [5]–[7], can be hardly compensated using digital signal processing (DSP), and severely degrades the performance of optical communications.

In this paper, the EEPN effect is studied in the 128-Gbaud dual-polarization 16-ary quadrature amplitude modulation (DP-16QAM) Nyquist-spaced multi-channel optical transmission system, with electronic dispersion compensation (EDC) and digital nonlinearity compensation (NLC), based on numerical simulations and the Gaussian noise (GN) model [8]–[10].

II. Analytical Model

Under EDC and NLC, the effective signal-to-noise ratio (SNR) of a Nyquist-spaced multi-channel optical system, influenced by the EEPN, can be expressed as [7]–[9]

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

$$\mathrm{SNR}_{\mathrm{NLC}} = \frac{P}{P_{\mathrm{ASE}} + P_{\text{Signal-ASE}} + \sigma^2_{\mathrm{EEPN}} \cdot P + P_{\text{Signal-EEPN}}} \quad (2)$$

where P donates the launch power of signals, P_{ASE} represents the ASE noise generated in the erbium-doped optical fiber amplifier (EDFA), P_{NLI} is the signal-signal interference from the nonlinear Kerr effect, σ^2_{EEPN} is the variance of the EEPN, $P_{\mathrm{Signal-ASE}}$ is the signal-ASE interaction, and $P_{\mathrm{Signal-EEPN}}$ is the interaction between signals and EEPN [7], [8].

III. Transmission Setup

To explore the impact of the EEPN in EDFA-amplified long-haul wavelength division multiplexing (WDM) optical fiber communication system, numerical simulations have been carried out with a system setup shown in Fig. 1. A 128-GHz spaced laser comb was employed as the transmitter laser source. Data sequences in all channels are random and independent. Split-step Fourier simulations based on the Manakov equation [11], [12] are performed for the transmission link with standard single mode fibers (SSMFs). The local oscillator (LO) laser with linewidths of 0 Hz and 100 kHz is operated in the coherent

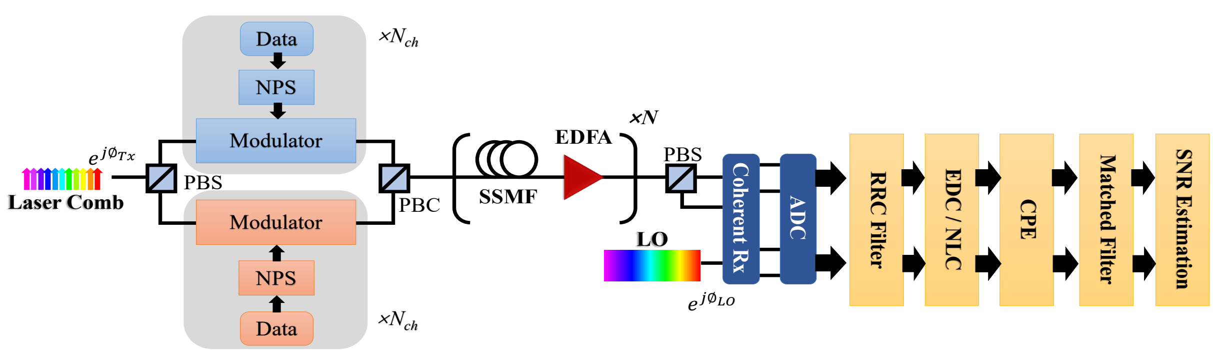

Fig. 1 Schematic of DP-16QAM Nyquist-spaced multi-channel long-haul optical fiber communication system using EDC and NLC. NPS: Nyquist pulse shaping; PBS: polarization beam splitter; PBC: polarization beam combiner.

detection. The EDC employs a frequency domain equalizer [13], and the NLC uses the reverse split-step Fourier solution of the Manakov equation [14]. An ideal carrier phase estimation (CPE) [15] is applied to fully compensate the laser phase noise. Polarization mode dispersion (PMD) [16] and laser frequency offset are neglected. Detailed parameters can be found in Table I.

TABLE II
SYSTEM PARAMETERS

Parameters	**Values**
Center wavelength (nm)	1550
Data rate (GBaud)	128
Attenuation coefficient (dB/km)	0.2
CD coefficient (ps/nm/km)	17
Nonlinear coefficient (1/W/km)	1.2
EDFA noise figure (dB)	4.5
Total fiber length (km)	30×80
Number of channels	{1, 5}
Modulation format	DP-16QAM
Roll-off factor	0.1%

IV. RESULTS AND DISCUSSIONS

Fig. 2 shows the central channel performance as a function of the signal launch power per channel in the single-channel 128-Gbaud DP-16QAM 2400 km optical transmission system. Solid and dotted lines represent analytical results for NLC and EDC cases, respectively, and markers denote simulation results. A high consistency can be observed between model results and simulations, which validates the accuracy of the GN-EEPN model. It is found that the peak SNR in the system is degraded due to EEPN by over 4 dB, in the case of NLC. Such obvious degradation reveals the vital deterioration, originating from the EEPN, in the long-haul optical systems, especially for signals transmitted at a relatively high data rate. Similar phenomena can be observed in Fig. 3, where theoretical and simulation results of the 128-Gbaud DP-16QAM 5-channel Nyquist-spaced 2400 km optical transmission are presented. The accuracy of the model and the great performance degradation accounting for the EEPN are also demonstrated in the multi-channel transmission system.

V. CONCLUSIONS

In this work, the impact of EEPN is investigated in the 128-Gbaud DP-16QAM multi-channel Nyquist-spaced long-haul optical transmission system. The significant degradation of the system performance due to EEPN has been demonstrated. This paper provides an in-depth insight into the design of long-haul high data rate multi-channel coherent optical transmission systems, which will be one of the major constructions in the next-generation telecommunication infrastructure.

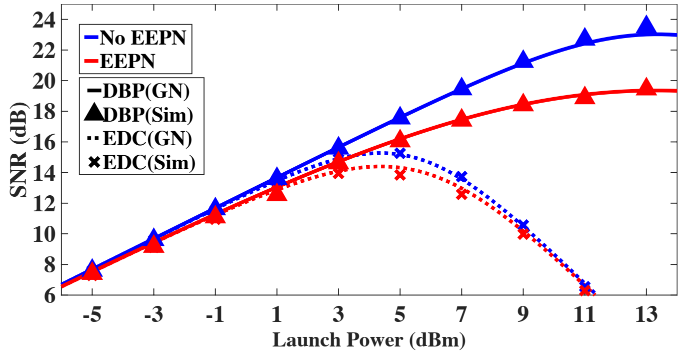

Fig. 2 The SNR of the central channel as a function of the launch power per channel in the 128-Gbaud DP-16QAM single-channel 2400 km optical transmission system.

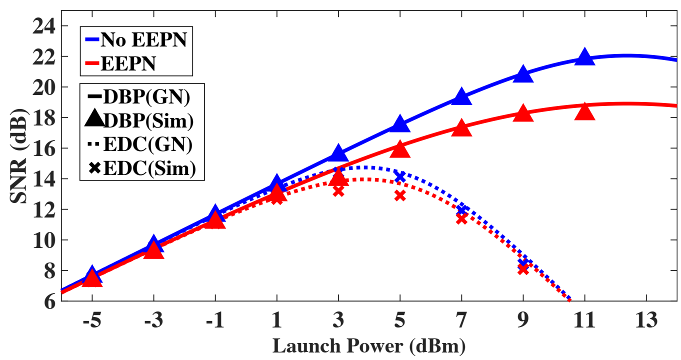

Fig. 3 The SNR of the central channel as a function of the launch power per channel in the 128-Gbaud DP-16QAM 5-channel Nyquist-spaced 2400 km optical transmission system.

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REFERENCES

[1] T. Xu et al., Opt. Express, vol. 29, no. 11, pp. 17428–17439, 2021.
[2] Z. Liu et al., Opt. Express, vol. 30, no. 7, pp. 11345–11359, 2022.
[3] T. Xu et al., Opt. Express, vol. 29, no. 24, pp. 39611–39632, 2021.
[4] D. Semrau et al., J. Light. Technol., vol. 36, no. 3, pp. 695–702, 2018.
[5] A. Kakkar et al., J. Light. Technol., vol. 33, no. 23, pp. 4834–4841, 2015.
[6] W. Shieh et al., Opt. Express, vol. 16, no. 20, pp. 15718–15727, 2008.
[7] C. Jin et al., J. Light. Technol., vol. 39, no. 14, pp. 4646–4653, 2021.
[8] P. Poggiolini et al., J. Light. Technol., vol. 33, no. 2, pp. 459–473, 2015.
[9] P. Poggiolini et al., IEEE Photonics Technol. Lett., vol. 23, no. 11, pp. 742–744, 2011.
[10] P. Poggiolini et al., J. Light. Technol., vol. 35, no. 3, pp. 458–480, 2017.
[11] D. Marcuse et al., J. Light. Technol., vol. 15, no. 9, pp. 1735–1746, 1997.
[12] G. Bosco et al., IEEE Photonics Technol. Lett., vol. 12, no. 5, pp. 489–491, 2000.
[13] E. Ip et al., J. Light. Technol., vol. 26, no. 20, pp. 3416–3425, 2008.
[14] V. Oliari et al., J. Light. Technol., vol. 38, no. 12, pp. 3114–3124, 2020.
[15] T. Xu et al., Sci. Rep., vol. 5, p. 13990, 2015.
[16] G. P. Agrawal, Fiber-Optic Communication Systems, 3rd ed. Hoboken, NJ, USA: Wiley, 2012.