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# Influence of Equalization Enhanced Phase Noise on Digital Nonlinearity Compensation in Nyquist-spaced Superchannel Transmission Systems

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## ABSTRACT

In digital signal processing (DSP) based coherent optical communication systems, the effect of equalization enhanced phase noise (EPPN) will seriously degrade the transmission performance of high-capacity optical transmission system. In this paper, we have investigated the influence of EPPN on 9-channel 32-Gbaud dual-polarization 64-ary quadrature amplitude modulation (DP-64QAM) Nyquist-spaced superchannel optical field trial by using electronic dispersion compensation (EDC) and multi-channel digital backpropagation (MC-DBP). The deteriorations caused by EPPN on the signal-to-noise-ratio (SNR) and achievable information rates (AIRs) in high-speed optical communication systems have been studied. The system performance versus back-propagated bandwidth under different laser linewidth have also been demonstrated. The SNR penalty due to the distortion of EPPN achieves  $\sim 5.11$  dB when FF-DBP is implemented, which informs that FF-DBP is more susceptible to EPPN, especially when the LO laser linewidth is larger. The system AIR versus different transmission distance under different EPPN interference using EDC-only and MC-DBP have also been evaluated, which show that there is a trade-off on the selection of lasers and back-propagated bandwidths to achieve a target AIR.

**Keywords:** Laser phase noise, electronic dispersion compensation, fiber nonlinearities, multi-channel digital back-propagation, equalization enhanced phase noise

## 1. INTRODUCTION

Currently, optical fiber transmission network carries over 95% of the data traffic, the number of devices connected to the IP network continues to increase globally, which poses a severe challenge to the carrying capacity of the optical fiber transmission network <sup>1</sup>. The spectral efficiency (SE) and the capacity of the coherent optical transmission system have been promoted through Nyquist-spaced superchannel transmission systems, advanced modulation formats (MF), space division multiplexing, and machine learning techniques <sup>2-9</sup>. Together with the advances in high-speed digital signal processing (DSP) techniques, the transmission impairment such as the chromatic dispersion (CD), polarization mode dispersion (PMD), laser phase noise (LPN), and fiber nonlinearities (FNLs) due to the optical Kerr effect, can be separately suppressed <sup>10-15</sup>. However, equalization enhanced phase noise (EPPN) originated from the interplay between LPN and electronic dispersion compensation (EDC) module cannot be easily equalized. A few studies regarding EPPN have been reported for linear optical communication systems, where fiber nonlinearities were neglected. It has been demonstrated that EPPN as a source of significant degradation in the performance of transmission systems, usually scales with the fiber dispersion, the linewidth of the local oscillator (LO) or the transmitter (Tx) laser, modulation format and symbol rate <sup>16-18</sup>. The nonlinear effect is one of the main detrimental factors restricting the information capacity of modern optical fiber communication systems. To date, digital backpropagation (DBP) is an effective nonlinearity

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compensation (NLC) technique which can compensate CD and NLI simultaneously, it is modeled by backward propagating signals through an optical fiber using the split-step Fourier method (SSFM) in the digital domain<sup>19</sup>. Yet, the influence of EEPN on the performance of superchannel transmission using multi-channel DBP (MC-DBP) has not been comprehensively investigated. Actually, EEPN can seriously degrade the performance of the schemes where significant CD has to be compensated over the entire superchannel bandwidth simultaneously, for example in the case of the full-field DBP (FF-DBP)<sup>20,21</sup>. Consequently, it is of great significance to investigate the influence of EEPN on the MC-DBP-based nonlinear compensation in Nyquist-spaced superchannel transmission systems.

In this paper, we intend to review and discuss the influence of EEPN on nonlinear Nyquist-spaced superchannel transmission systems by using EDC and MC-DBP. Numerical simulations have been carried out in a 9-channel 32-Gbaud dual-polarization 64-ary quadrature amplitude modulation (DP-64QAM) Nyquist-spaced wavelength division multiplexing (WDM) optical field trial using the EDC, the single-channel, the partial-bandwidth and the FF-DBP with and without the interference of EEPN. The deteriorations caused by EEPN on achievable information rates (AIRs) in high-speed optical communication systems have been studied. Also, the system performance versus back-propagated bandwidth under different laser linewidth has been demonstrated. It is found that EEPN significantly deteriorates the performance of the communication systems, especially in the case of FF-DBP. The SNR degradation due to the distortion of EEPN reaches ~5.11 dB when FF-DBP is implemented, which indicates that FF-DBP is more susceptible to EEPN, especially when the LO laser linewidth is larger. Finally, the system AIR versus different transmission distance under different EEPN interference using EDC-only and MC-DBP have also been demonstrated, which show that there is a trade-off on the selection of lasers and back-propagated bandwidths to achieve a target AIR.

## 2. PRINCIPLES AND TRANSMISSION SETUP

### 2.1 Principle of equalization enhanced phase noise

We take a post equalization scheme into consideration which is demonstrated in Figure 1, the ideal carrier phase estimation (CPE) is utilized for the compensation of LPN, the dispersion compensation module (either EDC or MC-DBP) is applied prior to the CPE module. In this configuration, the LPN generated by transmitter laser passes through both the fiber and the EDC module, so the net dispersion experienced by Tx PN is almost zero. However, the LPN from the LO laser goes through the EDC module only, which is severely dispersed without extra compensation. Therefore, the LO phase noise will interplay with the EDC module to converse the phase noise to amplitude noise, and the induced LOEEP N will significantly affect the performance of long-haul high speed optical transmission systems.

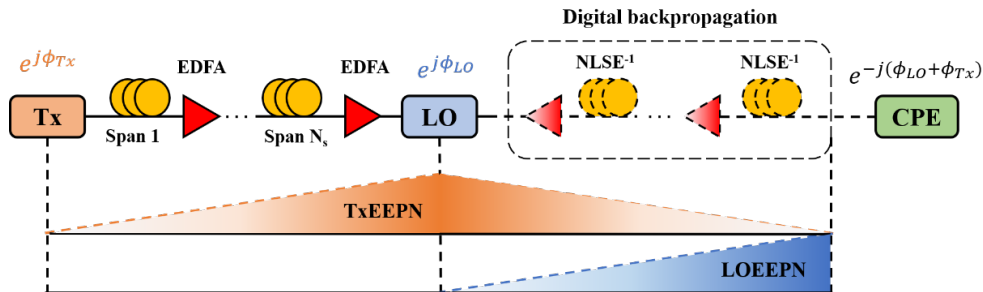


Figure 1. Schematic of the formation process of EEPN using digital compensation techniques.

It has been reported that the distortion of EEPN scales with the accumulated CD, the linewidth of the LO laser, and the symbol rate of the transmission system<sup>17,22</sup>. The noise variance of the EEPN can be expressed as follows:

$$\sigma_{EEP N}^2 = \frac{\pi\lambda^2}{2c} \cdot \frac{D \cdot L \cdot \Delta f_{LO}}{T_s} \quad (1)$$

where  $\lambda$  is the central wavelength of the transmitted optical carrier wave,  $c$  is the speed of light in vacuum,  $D$  is the chromatic dispersion coefficient of the transmission fiber,  $L$  is the total length of the fiber link,  $\Delta f_{LO}$  denotes the 3-dB LO laser linewidth, and  $T_s$  represents the symbol period of the optical field-trial system.

Therefore, the whole PN variances in the proposed transmission system considering the interference of EEPN can be summarized as

$$\sigma_{Total}^2 = \sigma_{Tx}^2 + \sigma_{LO}^2 + \sigma_{EEP}^2 + 2\rho\sigma_{LO}\sigma_{EEP} \approx \sigma_{Tx}^2 + \sigma_{LO}^2 + \sigma_{EEP}^2 \quad (2)$$

$$\sigma_{Tx}^2 = 2\pi\Delta f_{Tx} T_s \quad (3)$$

$$\sigma_{LO}^2 = 2\pi\Delta f_{LO} T_s \quad (4)$$

where  $\sigma_{Tx}^2$  and  $\sigma_{LO}^2$  represent the PN variances of the Tx and the LO lasers, respectively,  $\Delta f_{Tx}$  is the Tx laser's 3-dB linewidth, and  $\rho$  is defined as the correlation coefficient between the EEPN and the intrinsic LO phase noise.

## 2.2 Mutual information and achievable information rate estimation

Mutual information (MI) as an indicator of channel capacity is constrained by the Shannon limit in a channel with additive white Gaussian noise (AWGN)<sup>3</sup>. For a dual-polarization discrete QAM signal input distribution, MI can be defined as

$$MI = \frac{2}{M} \sum_{x \in X} \int_C P_{Y|X}(y|x) \log_2 \frac{P_{Y|X}(y|x)}{\frac{1}{M} \sum_{x' \in X} P_{Y|X}(y|x')} dy \quad (5)$$

where  $X = [X_1, \dots, X_M]$  is the set of transmitted random symbols,  $C$  is the set of complex numbers,  $M = |X| = 2^m$  denotes the cardinality of the  $M$ -QAM constellation with the number of bits per symbol  $m$ .  $P_{Y|X}(y|x)$  denotes the zero-mean complex-valued Gaussian conditional probability density function.

The AIR is an indicator to characterize the number of information bits per symbol that can be reliably transmitted through the channel<sup>23</sup>. The AIR of the DP-64QAM transmission system can be defined as

$$AIR = MI \cdot R_s \cdot N_{ch} \quad (6)$$

where  $N_{ch}$  is the number of sub-channel in the superchannel transmission system,  $R_s$  denotes the symbol rate of the transmitted signal.

## 2.3 Transmission system and field link

Table 1. system parameters of the 820 km field link.

Parameters	Value
Center wavelength	1550 nm
CD coefficient	17 ps/nm/km
Nonlinear coefficient	1.21/W/km
Symbol rate	32 GBaud
Channel spacing	32 GHz
Number of Channels	9
EDFA noise figure	4.5 dB
Roll-off factor	0.1%

Figure 2 shows the numerical simulation system of the 9-channel 32-Gbaud DP-64QAM Nyquist-spaced optical system, to emulate the field trial installed in the east coast of Sweden using the EDC or the MC-DBP<sup>24</sup>. The optical fiber link is the 820 km standard single-mode fiber (SSMF) installed in the east coast of Sweden. In the transmitter, a 9-line 32-GHz spaced laser comb with a center wavelength of 1550 nm is employed as the phase-locked optical carrier, and the comb lines are optically demultiplexed before the I-Q modulators. The pseudo-random binary sequence (PRBS) data with a pattern length of  $2^{16}$  are generated from a pattern generator and then a roll-off of 0.1% root-raised cosine (RRC) filter is employed to perform Nyquist pulse shaping (NPS). Subsequently, the 9-channel WDM optical carriers are modulated by in-phase and quadrature (I-Q) modulators, respectively. The numerical simulation is based on the split-step Fourier

solution of the Manakov equation with a logarithmic step-size distribution. Erbium-doped optical fiber amplifier (EDFA) is employed in the loop to compensate for the loss in the optical fiber.

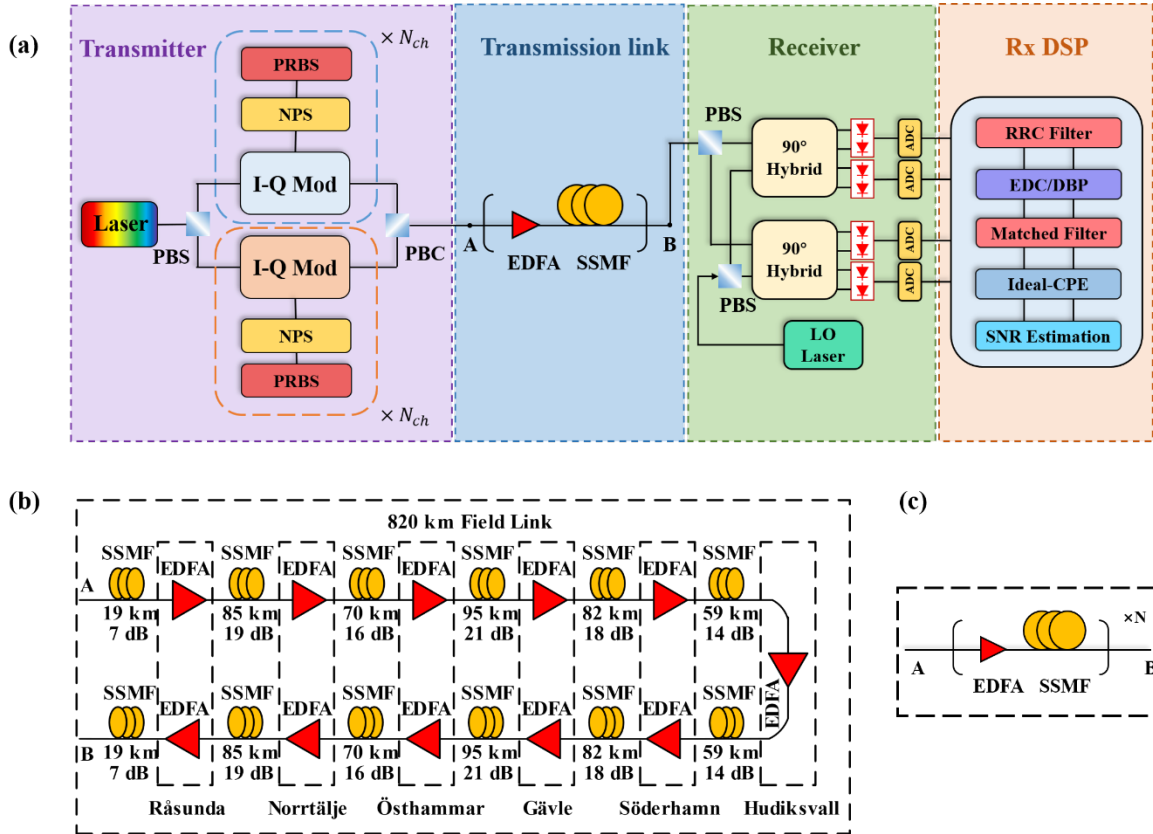


Figure 2. Transmission setup of the proposed scheme. (a) Configuration of the 9-channel 32-Gbaud DP-64QAM optical fiber communication system using the EDC or the MC-DBP. (b) Field link of the coherent transmission over 820 km installed SSMF in Sweden. (c) Optical fiber recirculation loop by using EDFA amplifier.

At the receiver, the signals are mixed with the LO laser to achieve a synchronous detection of all the in-phase and quadrature signal components in each polarization over the whole superchannel bandwidth. In the DSP module, the EDC is carried out using a frequency domain equalizer and MC-DBP is realized using the reverse split-step Fourier method of Manakov equation. The RRC filter is applied to select the MC-DBP bandwidth, and also to remove the out of band noise. The matched filter is utilized to select the interested channel, and an ideal CPE is employed to isolate the influence of EEPN from the intrinsic laser phase noise. Finally, the SNR is estimated to evaluate the performance of the transmission system. The frequency offset and polarization mode dispersion (PMD) are neglected. Detailed parameters of the transmission system are given in Table 1.

### 3. RESULTS AND ANALYSES

The performance of the 9-channel 32-Gbaud Nyquist-spaced DP-64QAM transmission system is illustrated in Figure 3, where the DBP is applied with three compensation bandwidths: 32 GHz, 160 GHz and 288 GHz, respectively. It can be seen in Equation (1) that the distortion of EEPN scales linearly with laser linewidth, so the linewidth of LO laser is used to measure the deterioration of EEPN. Figure (3a) provides the SNR versus optical launch power under EDC and MC-DBP with and without the interference of EEPN. When EEPN is not considered, the linewidth of the lasers was set as 0 Hz. In the presence of EEPN, both the Tx laser and LO laser linewidths are set as 500 kHz. For the EDC case, it is found that the peak SNR with EEPN is  $\sim 0.93$  dB lower than that without EEPN. When the partial bandwidth DBP is applied, the gaps are  $\sim 1.05$  dB and  $\sim 1.66$  dB for the 1-channel and 5-channel DBP, respectively. However, the SNR penalty due to the distortion of EEPN reaches  $\sim 5.11$  dB in contrast to FF-DBP. From the aforementioned results, FF-DBP is the most

susceptible to EEPN compared to the single-channel and the partial-bandwidth DBP. This is because the phase change in the DBP (actually the dispersion compensation) filter increases quadratically with the increase of the signal bandwidth.

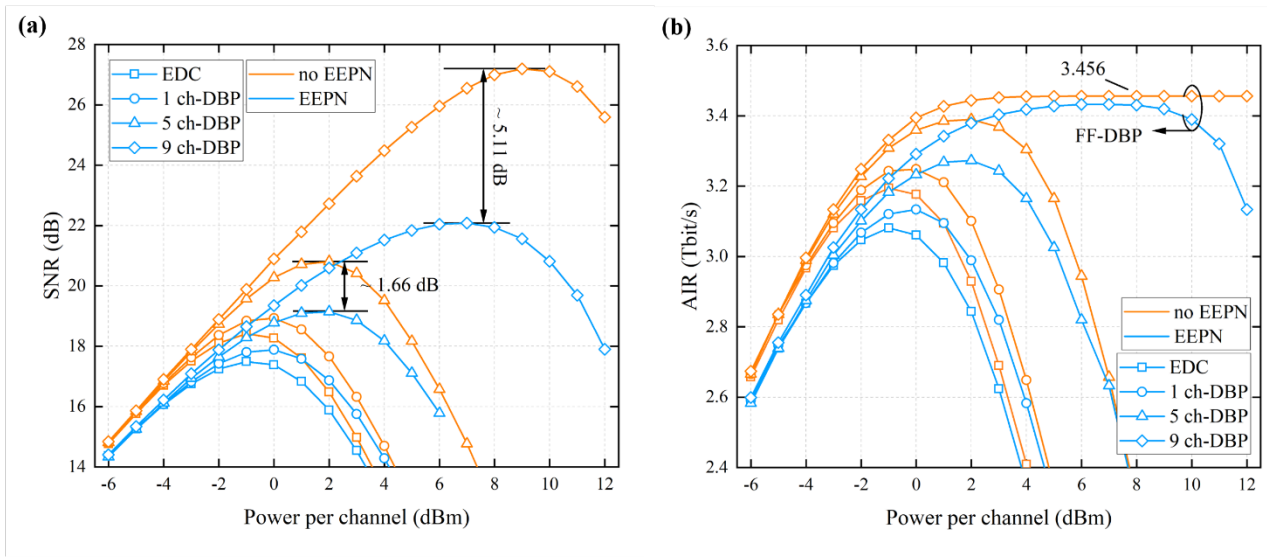


Figure 3. Simulation result for DP-64QAM coherent system in 820 km field link with and without the interference of EEPN. (a) SNR versus optical launch power. (b) AIR versus optical launch power.

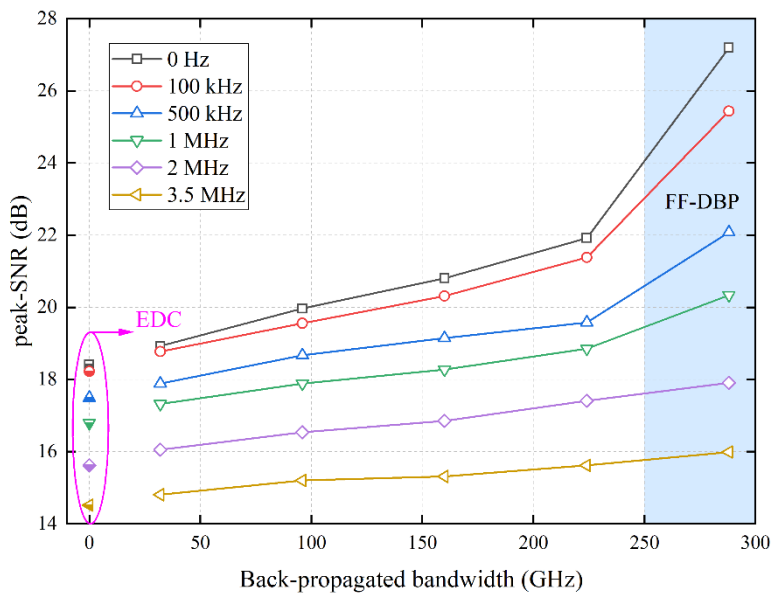


Figure 4. The peak-SNR versus back-propagated bandwidth under different laser linewidths in the DP-64QAM 9-channel Nyquist-spaced transmission system.

In order to further evaluate the information rate of the transmission system, the AIRs are used to measure the performance. Figure 3(b) demonstrated the simulation result of AIRs versus optical launch power in the 820 km field link at different back propagated bandwidths with and without the interference of EEPN. It can be found that the highest gain in terms of AIRs come from the FF-DBP without EEPN, which is  $\sim 3.456$  Tbit/s. However, the information rate dropped by  $\sim 0.02$  Tbit/s due to the noise interference generated by EEPN when the FF-DBP is used. When the optical transmission system uses a larger bandwidth for communication, EEPN noise will have a greater decrease in the information rate of the system which uses the MC-DBP algorithm for NLC.

Figure (4) shows the peak-SNR versus back-propagated bandwidth under different laser linewidth in the DP-64QAM 9-channel Nyquist-spaced transmission system. The ‘0’ value of the back propagated bandwidth refers to the EDC-only case. Firstly, the peak SNR of the transmission system gradually increase benefit from the broaden in the compensation bandwidth range, the growth trend of peak SNR is basically linear before compensation bandwidth comes to 224 GHz. It can be observed that there is a sharp increase in the peak SNR when FF-DBP is implemented under the condition of no EEPN interference. However, the distortion caused by EEPN becomes more severe as the laser linewidth increases. Meanwhile, the influence is more obvious when the back propagated bandwidth is larger. The peak SNR decreased by  $\sim 1.75$  dB,  $\sim 5.11$  dB,  $\sim 6.85$  dB under full bandwidth compensation when the 100 kHz, 500 kHz, 1 MHz laser linewidth is used, respectively. The scheme of FF-DBP only obtains a peak SNR gain of  $\sim 1.19$  dB compared to 1-channel DBP under 3.5 MHz laser linewidth, but it increases the computational complexity by thousands of times. Therefore, compared to the scenario of the EDC-only and the partial bandwidth DBP, the transmission system is more susceptible to the EEPN interference in the case of FF-DBP, especially when the LO laser linewidth is large.

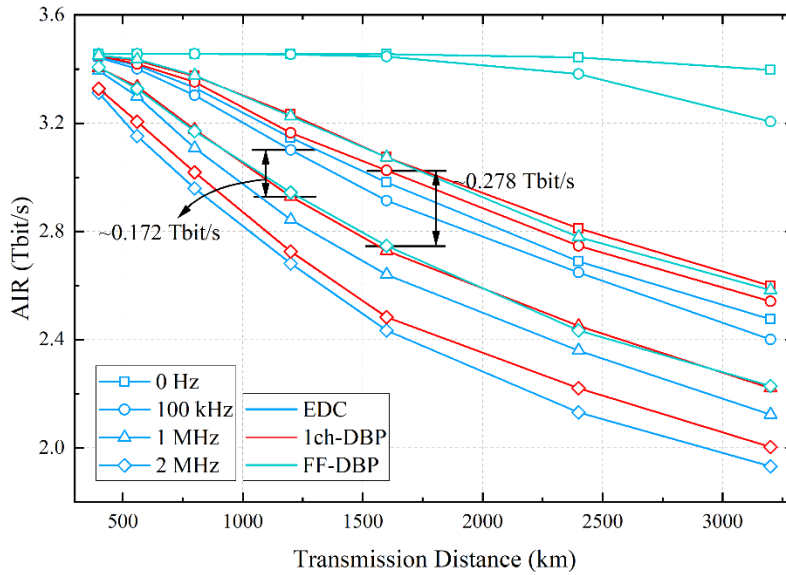


Figure 5. Simulation result of AIRs versus transmission distance under different laser linewidth in the DP-64QAM 9-channel Nyquist-spaced transmission system by using EDC and MC-DBP.

Finally, in order to evaluate the damage caused by EEPN noise to long-haul communication system, the AIRs versus different transmission distance based on the fiber recirculation loop in Figure 2(c) under different EEPN interference using EDC-only and MC-DBP have been also evaluated, which is illustrated in Figure 5. It can be seen that the DP-64QAM 9-channel Nyquist-spaced transmission system can almost maintain the highest transmission AIR with the transmission distance up to 2400 km using FF-DBP without EEPN interference. However, the highest AIR can only be kept up to 1600 km due to the EEPN noise when the laser linewidth is 100 kHz, even at the transmission distance of 1600 km under the FF-DBP equalization scheme, the EEPN caused by the 1 MHz and 2 MHz laser linewidths reduces AIR by  $\sim 0.38$  Tbit/s and  $\sim 0.71$  Tbit/s, respectively. It is also shown that, at the transmission distance of 1200 km the EDC-only using 100 kHz laser linewidth outperforms the 1-channel DBP when the laser linewidth is 1 MHz, and at the transmission distance of 1600 km the 1-channel DBP using 100 kHz laser linewidth outperforms FF-DBP using 2 MHz laser linewidth. This offers a trade-off on the selection of lasers and back-propagated bandwidths to achieve a target AIR.

#### 4. CONCLUSIONS

In this paper, the influence of EEPN on the Nyquist-spaced DP-64QAM optical field transmission system using EDC and MC-DBP have been evaluated, which contributes to improving existing knowledge of high-order modulation setup. The SNR and AIRs of the transmission system using the EDC, the partial bandwidth, and the full-field DBP were comparatively evaluated with and without the interference of EEPN. Also, the system performance versus back-



propagated bandwidth under different laser linewidth have also been demonstrated, which shows that the transmission system is more susceptible to the EEPN interference in the case of FF-DBP compared to the scenario of the EDC-only and the partial bandwidth DBP, especially when the LO laser linewidth is larger. Finally, the system AIR versus different transmission distance under different EEPN interference using EDC-only and MC-DBP show that there is a trade-off on the selection of lasers and back-propagated bandwidths to achieve a target AIR.

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