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# Digital Back-Propagation in Optical Fiber Communication Systems Considering Equalization Enhanced Phase Noise

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## ABSTRACT

The effect of equalization enhanced phase noise (EEPN) will be introduced in digital signal processing (DSP) based coherent optical communication systems. The EEPN will seriously degrade the transmission performance of a high-capacity optical transmission system. In this work, the influence of EEPN on the performance of dual-polarization 16-ary quadrature amplitude modulation (DP-16QAM) optical transmission system using the electrical dispersion compensation (EDC), the single-channel digital back-propagation (DBP), the partial-bandwidth DBP and the full-field DBP (FF-DBP) were comparatively evaluated with and without considering distortions from the EEPN. Deteriorations on achievable information rates (AIRs) and modulation error ratios (MERs) of optical communication systems due to EEPN have also been assessed. Numerical results indicate that the transmission performance of coherent optical systems can be significantly degraded by the EEPN, especially when FF-DBP is used for the nonlinearity compensation. The larger the linewidth of the local oscillator (LO) laser is, the more serious the degradation caused by EEPN is. This deterioration leads to a decrease in optimal launch powers, AIRs and MERs in the long-haul optical communication systems. In the DP-16QAM transmission system, because of the interference of the EEPN generated by the LO laser with a linewidth of 1 MHz, the degradations on the AIR and MER are 0.15 Tbit/s and 4.15 dB in the case of FF-DBP, respectively. It can also be concluded that, for coherent optical systems with long transmission distances and high symbol rates, the compensation bandwidth and the computational complexity of MC-DBP in the DSP module can be significantly reduced by using narrower-linewidth LO lasers.

**Keywords:** Laser phase noise, Electronic dispersion compensation, Fiber nonlinearities, Multi-channel digital back-propagation, Equalization enhanced phase noise

## 1. INTRODUCTION

With the advent of the information era, the demand for high-speed and large-capacity optical communications has been dramatically increased. The transmission distance and the information capacity of the optical fiber communication systems have been greatly improved through a series of revolutionary technological breakthroughs [1–4]. For a certain communication bandwidth, higher achievable information rates (AIRs) can be obtained by utilizing the Nyquist-spaced superchannels and advanced modulation formats. Nevertheless, this rapid expansion is faced with several bottlenecks, the performance of long-haul superchannel transmission systems is severely limited by the chromatic dispersion (CD), the polarization mode dispersion (PMD), the laser phase noise (LPN) and Kerr fiber nonlinearity (FNL), which resulting in great restrictions on the AIRs [4,5]. The use of digital signal processing (DSP)-based electrical dispersion compensation (EDC) instead of dispersion compensation fiber (DCF) can greatly reduce the cost of practical facilities, and can improve the flexibility and portability of the optical communication modules [6–8]. In addition, the amplifier noise and the FNLs in the optical fiber are also reduced. Nonlinear impairments mitigation among channels are achieved by utilized multi-channel digital backpropagation (MC-DBP) at different backpropagated bandwidths. A number of research works with respect to MC-DBP have been investigated [9–14]. Besides, a large amount of phase noise introduced by the linewidth of

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the laser is very harmful to the phase modulated signal, while the carrier frequency offset and the phase noise can be eliminated by carrier phase estimation (CPE) in a coherent receiver [8,14].

However, the information capacity of DSP-based coherent transmission systems using advanced modulation formats are severely affected by the equalization enhanced phase noise (EEPN) which arises from the interaction between the LPN and the EDC module. Distortions from EEPN will result in a significant degradation of the system performance. Tremendous investigations with EEPN have been carried out for linear optical transmission systems [7,14–22]. It is indicated that the EEPN, a source of severe performance degradation in long-haul transmission systems, increases with the accumulated CD, local oscillator (LO) laser linewidth, the modulation format and the symbol rate of the system [7,15,19]. Yet, so far, the effects of EEPN in optical superchannel transmission systems considering FNL and nonlinearity compensation (NLC) were rarely reported [14,21]. Actually, the information capacity of such superchannel transmission schemes will be severely degraded by the EEPN, especially when CD has to be compensated simultaneously over the entire superchannel bandwidth. In this way, the influence of EEPN must be taken into account when the optimization of the optical fiber network is performed. Consequently, it is of importance to study the performance of nonlinear compensation using MC-DBP in superchannel transmission systems under the degradation of EEPN.

Here, we demonstrate the performance of EDC and MC-DBP under different LO laser linewidths with respect to bit-error-rates (BERs), AIRs and modulation error ratio (MERs) in the DP-16QAM optical field transmission system. Numerical simulations have been carried out in a 9-channel 64-Gbaud Nyquist-spaced wavelength division multiplexing (WDM) optical communication system using the EDC, the single-channel, the partial-bandwidth and the full-field DBP with and without the interference of EEPN. Simulation results indicate that the transmission performance of coherent optical systems can be significantly deteriorated by the EEPN, especially when the FF-DBP is used for nonlinearity compensation. It is also demonstrated that in practical high-capacity optical communication systems, the compensation bandwidth and computational complexity of MC-DBP in the DSP modules can be significantly reduced by using narrower-linewidth LO lasers.

## 2. TRANSMISSION SETUP AND PRINCIPLES

### 2.1 Transmission Setup

Figure 1 shows the transmission setup for 9-channel 64-Gbaud Nyquist-spaced optical field trial using DP-16QAM over the 820 km standard single-mode fiber (SSMF) installed in the east coast of Sweden [23].

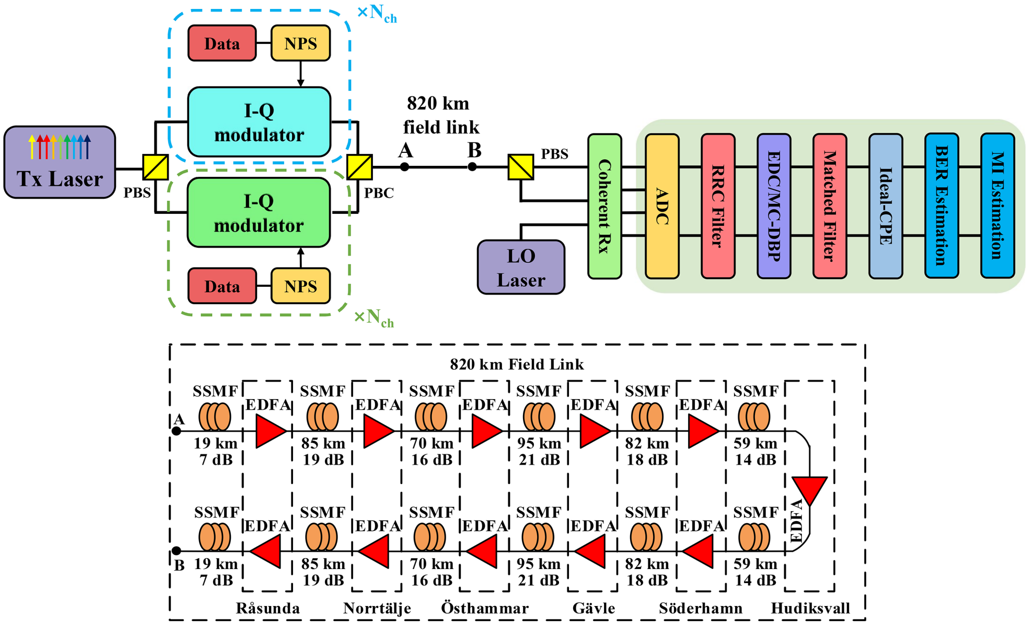

Figure 1. Simulation setup for 9-channel 64-Gbaud Nyquist-spaced DP-16QAM coherent transmission system and optical field link over the 820 km installed SSMF.

In the transmitter (Tx), a 9-line 64-GHz spaced laser comb with a center wavelength of 1550 nm serves as the phase-locked optical carrier for each WDM sub-channel. Subsequently, the 9-channel WDM optical carriers are modulated by 64-Gbaud DP-16QAM signals via in-phase and quadrature (I-Q) modulators, respectively. The modulated data sequence employed the pseudo-random binary sequence (PRBS) with a pattern length of $2^{16}$. The Nyquist pulse shaping (NPS) is performed through a root raised cosine (RRC) filter with a roll-off coefficient of 0.1%. After the modulation, two orthogonally polarized signal sequences are injected into the optical field link. The signal propagation in 820 km SSMF is numerically simulated using the split-step Fourier method (SSFM) based on the nonlinear Schrödinger equation (NLSE) with a step size of 0.1 km to ensure its precision. The nonlinear coefficient of each fiber segment is set as 1.2 /w/km in all numerical simulations. The attenuation coefficient and the length of each segment of the field link are shown in the bottom of Figure 1. The loss of fiber during each span is compensated by the erbium-doped fiber amplifier (EDFA) with a noise figure of 5.0 dB. With a digital coherent receiver (Rx), the incoming signal is split into two orthogonal polarizations by the polarization beam splitter (PBS), and then the I-Q component is coherently mixed with the LO laser in each polarization state. After being sampled by the analog-to-digital converters (ADCs), an ideal RRC filter is used to remove out-of-band amplifier and channel noise and to control the bandwidth required for subsequent DBP algorithm. The signal impairment compensation is achieved using advanced DSP modules. The frequency domain equalizer (FDE) is utilized for the dispersion mitigation, while the DBP algorithm at different bandwidths is used for the NLC. The purpose of an ideal-CPE in the coherent receiver is to completely compensate the intrinsic laser phase noise [14,19]. The frequency offset and the PMD are neglected in all simulations.

### 2.2 Principle of Equalization Enhanced Phase Noise

As depicted in Figure 1, the CD compensation module is applied prior to the CPE module [14]. The LPN originates from the Tx laser experiences the 820 km SSMF and the dispersion compensation equalizer during the forward transmission and the DSP. Therefore, the interaction between phase noise from the Tx laser and the dispersion compensation equalizer is almost zero. However, the inherent LPN of the LO laser provides a pessimistic scenario since it experiences the CD compensation module only in the communication systems without using any optical dispersion compensation (OPC). Due to the non-exchangeability of the LPN and the CD, a new interference caused by the LO phase noise will be enhanced by the electric dispersion equalizer, and the phase noise will be converted into amplitude noise.

Previous studies have reported that the noise variance of EEPN increases with the accumulated dispersion in the fiber link, the linewidth of the laser and the symbol rate of the transmission system [7,8]. Mathematically, it can be described as follows:

$$\sigma_{EEPN}^2 = \frac{\pi\lambda^2}{2c} \cdot \frac{D \cdot L \cdot \Delta f_{LO}}{T_S} \tag{1}$$

where λ is the center wavelength of carrier laser, $c$ is the speed of light, $D$ is the CD coefficient of 820 km installed SSMF, which is set as 17 ps/nm/km in all simulations, $L$ is the total length of fiber link, $\Delta f_{LO}$ is the LO laser's 3-dB linewidth, and $T_S$ represents the symbol period of the optical field-trial system.

Consequently, the whole phase noise variances in a coherent optical communication system considering the interference of EEPN can be summarized as

$$\sigma_{\text{Total}}^2 = \sigma_{Tx}^2 + \sigma_{LO}^2 + \sigma_{EEPN}^2 + 2\rho\sigma_{LO}\sigma_{EEPN} \approx \sigma_{Tx}^2 + \sigma_{LO}^2 + \sigma_{EEPN}^2 \tag{2}$$

$$\sigma_{Tx}^2 = 2\pi\Delta f_{Tx} T_S \tag{3}$$

$$\sigma_{LO}^2 = 2\pi\Delta f_{LO} T_S \tag{4}$$

where $\Delta f_{Tx}$ is the Tx laser's 3-dB linewidth, $\sigma_{Tx}^2$ and $\sigma_{LO}^2$ denote the phase noise variances of the Tx and the LO lasers, respectively, and $\rho$ is defined as the correlation coefficient between the EEPN and the intrinsic LO phase noise. Previous research has established that $\rho \approx 0$ when the fiber length beyond 80 km [8].

### 2.3 Mutual information theory

In our numerical simulations, the code rate of the binary symmetric DP-16QAM transmission system can be expressed as

$$R_C = 1 + BER \cdot \log_2(BER) + (1 - BER) \cdot \log_2(1 - BER) \tag{5}$$

The AIR is a significant figure of merit that characterizes the net data rate that can be obtained using forward error correction (FEC) encoders in coded communication systems. The AIR of the DP-16QAM transmission system is denoted as

$$AIR = 2 \cdot \log_2(m) \cdot R_C \cdot R_S \cdot N_{\mathrm{ch}} \tag{6}$$

where $m$ is equal to 16, $2 \cdot \log_2(m) \cdot R_C$ is the mutual information (MI) of the transmission system, $N_{\mathrm{ch}}$ denotes the number of sub-channels in the superchannel transmission system, and the term $R_S$ refers to the symbol rate of the transmitted data.

The MER is used as the indicator to assess the capability of the Tx or the Rx in communication systems based on high-order digital modulation formats [24,25]. The MER is measured using the ratio between the average signal constellation power and the average constellation error power. The MER can alternatively be expressed as follows:

$$MER(dB) = 10\log_{10}\left(\frac{P_{signal}}{P_{error}}\right) \tag{7}$$

where $P_{error}$ is the root mean square (RMS) power of the error vector and $P_{signal}$ is the RMS power of the ideal transmitted signal.

## 3. SIMULATION RESULTS AND DISCUSSIONS

Numerical simulations were carried out for the 9-channel 64-Gbaud DP-16QAM transmission system over the 820 km field link. The DBP algorithm is implemented via solving the NLSE based on the reverse split-step Fourier method in the digital domain at different compensation bandwidth, which is set as 64 GHz, 320 GHz and 576 GHz, respectively. It is noted in Equation (1) that different laser linewidths will produce different EEPN variances, so here we use the linewidth of the LO laser to characterize the size of the EEPN. In all simulations, keep the linewidth of the Tx laser consistent with that of the LO laser. When EEPN is not considered, the linewidth of the lasers was set as 0 Hz. In the presence of EEPN, two scenarios were considered: (a) 100 kHz (common external cavity lasers), (b) 1 MHz (common distributed feedback lasers).

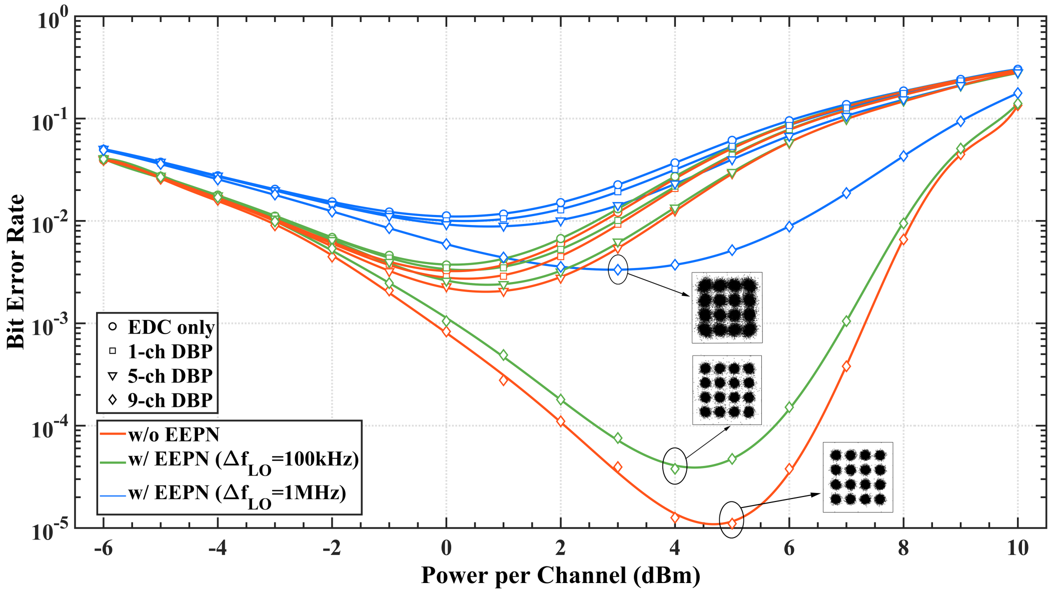

Figure 2. Simulated curves of BER versus optical launch power with (w/) and without (w/o) the interference of EEPN using different compensation bandwidth in the DP-16QAM system. Insets are the X-polarization constellation diagrams with FF-DBP under different LO linewidths.

Figure 2 provides the variation of BER versus optical launch power under different MC-DBP compensation bandwidths with and without the interference of EEPN, where the total fiber length is 820 km. From the graph above we can see that the optimal launch powers obtained are 0 dBm, 0 dBm, 1.0 dBm and 5.0 dBm without the interference of EEPN, the corresponding BERs are $3.27\times10^{-3}$ , $2.85\times10^{-3}$ , $2.29\times10^{-3}$ and $1.10\times10^{-5}$ when the EDC, the single-channel, the 5-channel and the full-field DBP are applied, respectively. As the LO linewidth increases to 100 kHz, the simulation results reveal that there has been a slight decline in the number of the optimal launch powers for the FF-DBP. The optimal launch power of the other three compensation methods remains unchanged. The corresponding BERs of the EDC, the signal-channel DBP, the 5-channel DBP and the FF-DBP rise to $3.72\times10^{-3}$, $3.49\times10^{-3}$, $2.41\times10^{-3}$ and $3.78\times10^{-5}$, respectively, compared to the case without any EEPN. The transmission performance becomes further worse, as shown in Figure 2, when a larger LO linewidth is used, the optimal launch powers for the EDC, the signal-channel DBP, and the 5-channel DBP still remain as before, respectively, yet the launch power of FF-DBP reaches its best point at 3 dB. Corresponding BERs move upwards to $1.12\times10^{-2}$ , $1.00\times10^{-2}$, $9.26\times10^{-3}$ and $3.34\times10^{-3}$ when the EDC, the single-channel DBP, the 5-channel DBP and the FF-DBP are applied, respectively. An increase of almost two orders of magnitude (from $1.10\times10^{-5}$ to $3.34\times10^{-3}$) of the optimal BER is achieved in the case of FF-DBP due to the impairment of EEPN. In contrast to FF-DBP, a BER increase of less than an order of magnitude (from $3.27\times10^{-3}$ to $1.12\times10^{-2}$) is achieved for EDC-only scheme. As presented in the insets of Figure 2, the constellation of FF-DBP with the LO laser linewidth of 1 MHz is much worse than that with the LO laser linewidth of 0 Hz and 100 kHz, respectively. Compared to the scenario of the EDC, the single-channel and the 5-channel DBP, the BER performance is more susceptible to the EEPN interference in the case of FF-DBP, especially when the LO laser linewidth is large.

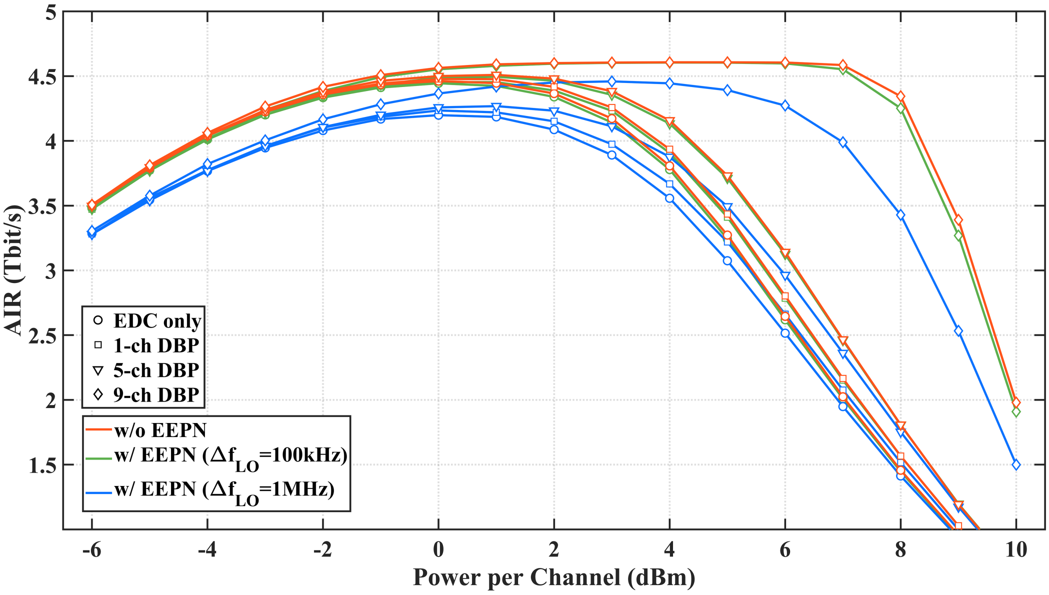

Figure 3. Simulated curves of AIR versus optical launch power with (w/) and without (w/o) the interference of EEPN using different compensation bandwidth in the DP-16QAM system.

In order to further characterize the transmission information rate of the communication system, we use AIR to measure its performance. The AIRs and optical launch powers under different MC-DBP compensation bandwidths with and without the interference of EEPN in the DP-16QAM transmission system are summarized in Figure 3. When there is no EEPN interference, for the scenarios of the EDC, the single-channel DBP, the 5-channel DBP and the FF-DBP, the optimum AIRs obtained in the system at their optimal launch powers are 4.46 Tbit/s, 4.48 Tbit/s, 4.51 Tbit/s and 4.61 Tbit/s, respectively. Compared to the case where there is no EEPN interference, the EEPN generated by the LO laser with a linewidth of 100 kHz has only a negligible effect on the case of the EDC and the MC-DBP. In contrary to the above cases, the use of the 1 MHz linewidth LO laser pose a heavy influence on the use of MC-DBP, especially for the case of FF-DBP. The value of the optimum AIR for the FF-DBP declines from 4.61 Tbit/s to 4.46 Tbit/s when the laser linewidth increases from 0 Hz to 1 MHz. Meanwhile, an interesting phenomenon can be observed that when the optical power is less than 2 dBm, the AIR with a laser linewidth of 100 kHz is 4.50 Tbit/s in the application of the 5-channel

DBP for NLC, which is slightly higher than the 4.46 Tbit/s obtained in the use of the FF-DBP when the LO laser linewidth is 1 MHz. Here we use the compensation bandwidth of MC-DBP as a parameter, this shows that to obtain a target information rate, the compensation bandwidth and computational complexity of MC-DBP in the DSP module can be significantly reduced by using a narrower-linewidth LO laser.

In addition, the MER is a method to quantify the constellation noise as seen in Figure 2 and it shows tremendous advantage in the ability to restore transmitted data of the long-haul communication system. Figure 4 illustrated the MER versus the optical launch power in the optical field link by applying the EDC and the MC-DBP. When there is no influence of EEPN, the maximum MER that can be obtained in FF-DBP is 19.41 dB. As the LO linewidth increases to 100 kHz, the maximum MER in the FF-DBP decreases to 18.67 dB. However, the maximum MER in the case of FF-DBP falls significantly to 15.26 dB when the laser linewidth rises to 1 MHz. As seen from Figure 4, the EEPN seriously reduces the MER of the communication system when the EDC and the MC-DBP are used for the impairment management. What stands out in the figure is that the EEPN degradation on the MER of FF-DBP with the LO linewidth of 1 MHz is the most serious in all investigated scenarios.

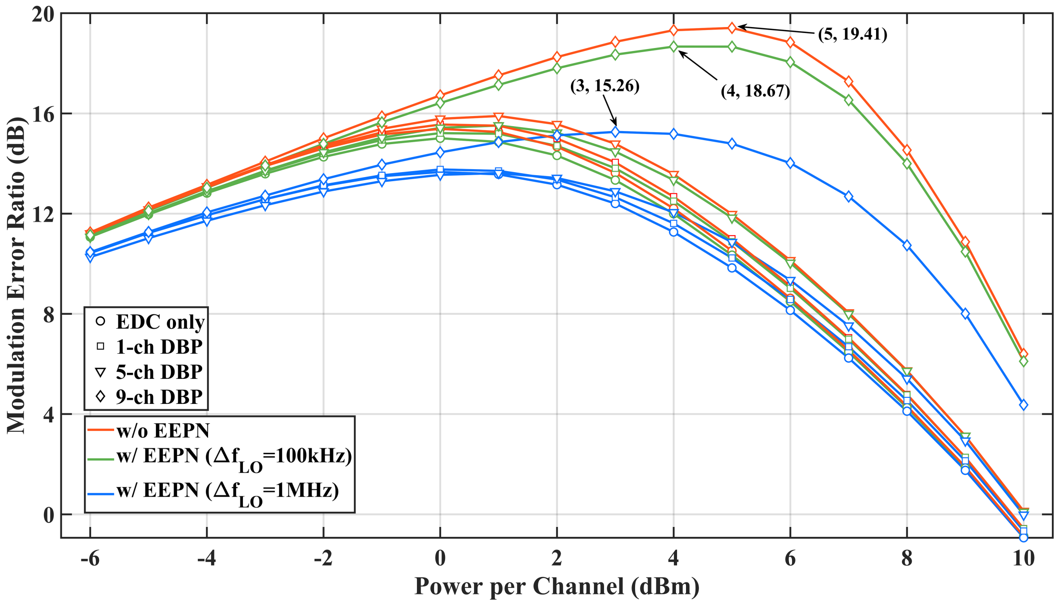

Figure 4. Simulated curves of MER versus optical launch power with (w/) and without (w/o) the interference of EEPN using different compensation bandwidth in the DP-16QAM system.

In the practical 820 km optical field trial discussed in this paper, the inherent LPNs generated from the Tx and the LO lasers have been fully compensated by the phase conjugate multiplication in the ideal-CPE module. In this case, the phase noise generated by the laser has been decorrelated with EEPN. Therefore, the performance degradation of AIR and MER is caused by EEPN and FNLs. It is noted that the dispersion compensation is carried out synchronously with the nonlinear compensation in MC-DBP algorithm. The aforementioned results demonstrated that EEPN has the greatest impact on FF-DBP in the above three nonlinear compensation schemes. The reason for this phenomenon is that the phase of the signal in the MC-DBP (the CD compensation) filter changes quadratically in the frequency domain. The relative frequency of the outer sub-channel is higher than the central sub-channel, so its phase change is greater and will produce a more considerable EEPN. Therefore, EEPN poses a more severe impairment in the case of FF-DBP. The interference from EEPN will cause the transmission BER to increase, and the optimal launch power of FF-DBP will also decrease with the increase of EEPN. Consequently, for coherent optical systems with the long-distance transmission, high symbol rate and electronic compensation dispersion, the impairments of EEPN put forward stricter requirements on the phase noise of the Rx laser (actually the linewidth of the laser) due to the existence of EEPN. Also, the restrictions of EEPN on the systems performance are more stringent in the use of higher-order modulation formats.

# 4. CONCLUSIONS

This paper has described the influence of EEPN on the BER, the AIR and the MER of Nyquist-spaced DP-16QAM optical field transmission system, which contributes to improving existing knowledge of high-order modulation setup. The performance of the transmission system using the EDC, the single-channel, the partial-bandwidth, and the full-field DBP were comparatively evaluated with and without the interference of EEPN. Deteriorations on the AIRs and MERs of communication systems due to the EEPN have also been assessed. Simulation results indicate that the transmission performance of coherent optical systems can be significantly degraded by EEPN, especially when FF-DBP is used for nonlinearity compensation. In the DP-16QAM transmission system, due to the interference of the EEPN generated by the LO laser with the linewidth of 1 MHz, the degradations on the AIR and MER, in the case of FF-DBP, are 0.15 Tbit/s and 4.15 dB, respectively. The EEPN induced degradations lead to a decrease in the optimal launch powers, the AIRs and the MERs in the high-capacity transmission systems. It is also seen that, in practical high-capacity optical communication systems, the compensation bandwidth and the computational complexity of MC-DBP in the DSP modules can be significantly reduced via the use of narrower-linewidth LO lasers.

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