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Influence of Spectral Broadening on Nonlinearity Compensation in Ultra-Wideband Optical Fiber Communications

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ABSTRACT

Optical fiber networks form the major part of the modern telecommunication infrastructure and are carrying over 95% of the Internet digital data. The increasing demand for higher data rates has promoted the development of higher-order modulation formats, denser wavelength multiplexing and more powerful signal processing. With the entire suppression of the chromatic dispersion, the polarization mode dispersion and the laser phase noise using digital signal processing, Kerr fiber nonlinearities become the main capacity barrier for optical communication systems, and digital back-propagation is generally applied to overcome such distortions. Kerr effects also result in the broadening of spectra of signals propagating in optical fibers, owing to intra- and inter-channel nonlinear interactions. This report shows that the spectral broadening effect is crucial for achieving an optimal performance of the digital back-propagation in wideband optical trasnmission systems.

Keywords: optical fiber communications, Kerr fiber nonlinearities, spectral broadening, digital back-propagation.

1. INTRODUCTION

Optical communication networks play a vital role in the technological infrastructure underpinning Internet traffic applications. Service providers and researchers worldwide are sparing no effort to increase the information capacity and security of optical telecommunication networks to support high-speed and reliable internet, data center, cloud computing, 5G and IoT systems [1]. Since the outbreak of COVID-19 the remote work, educations, meetings and social events, as well as medical diagnoses, pose urgent and huge demand on internet capacity and performance. Optical fibers carry over 95% of Internet data across continents and oceans and are expected to be the key technology to support the future IP traffic demand [2]. The increasing demand on higher data capacity has promoted the development and application of higher-order modulation formats, denser wavelength division multiplexing (WDM) and more powerful digital signal processing (DSP) techniques [3].

Nyquist-spacing and DSP-based coherent optical transmission has proved efficient in enhancing the information capacity, the spectral efficiency (SE) and the maximum reach of fiber communication systems. In such systems, the chromatic dispersion (CD), the polarization mode dispersion (PMD) and the laser phase noise (LPN) are well compensated using the DSP based electronic dispersion compensation (EDC), polarization equalizer and carrier phase estimation (CPE) algorithms, respectively [4-8]. Consequently, Kerr effects induced intra-channel and inter-channel fiber nonlinearities have become major fundamental capacity-limiting factors in optical communication systems [9,10]. Therefore, digital back-propagation (DBP) has been applied to suppress the Kerr nonlinearities and to increase the information capacity in such systems [11-13].

As shown in Fig. 1, a broadening effect of the data spectrum will be introduced during the signal propagation, due to the Kerr nonlinear interactions within the fiber medium [14,15]. The spectral broadening effect was studied and evaluated in optical communication systems with considerable intra- and inter-channel fiber nonlinearities [16-18]. The impact of the spectral broadening on the digital nonlinearity compensation in optical transmission systems was also investigated [19-21]. It was found in these reports that the received signal spectra were not necessarily matched to the transmitted ones any longer owing to this spectral broadening effect.

In this invited paper, the influence of Kerr-nonlinearity induced spectral broadening on the performance of DBP will be reviewed and discussed in wideband coherent optical communication systems, built on our previous work [19-22]. It is found that taking into account the spectral broadening effect is critical to achieve the optimal behavior of the digital back-propagation and this impact will become more important for outer transmission channels in the wideband communication systems.

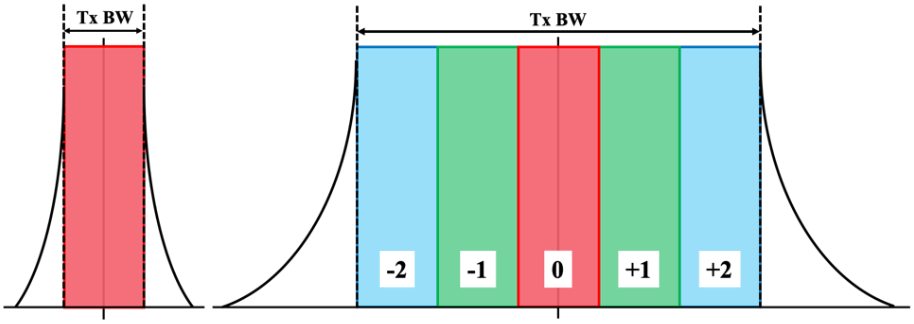

Figure 1. Diagram of Kerr fiber nonlinearity-induced spectral broadening effect in Nyquist-spaced optical communication systems (a) single-channel transmission system, (b) multi-channel transmission system. Tx BW: transmitted bandwidth.

2. OPTICAL TRANSMISSION SYSTEM

In this work, a coherent system of 9-channel 32-Gbaud Nyquist-spaced WDM dual-polarization 16-ary quadrature amplitude modulation (DP-16QAM) transmission has been implemented, as shown in Fig. 2.

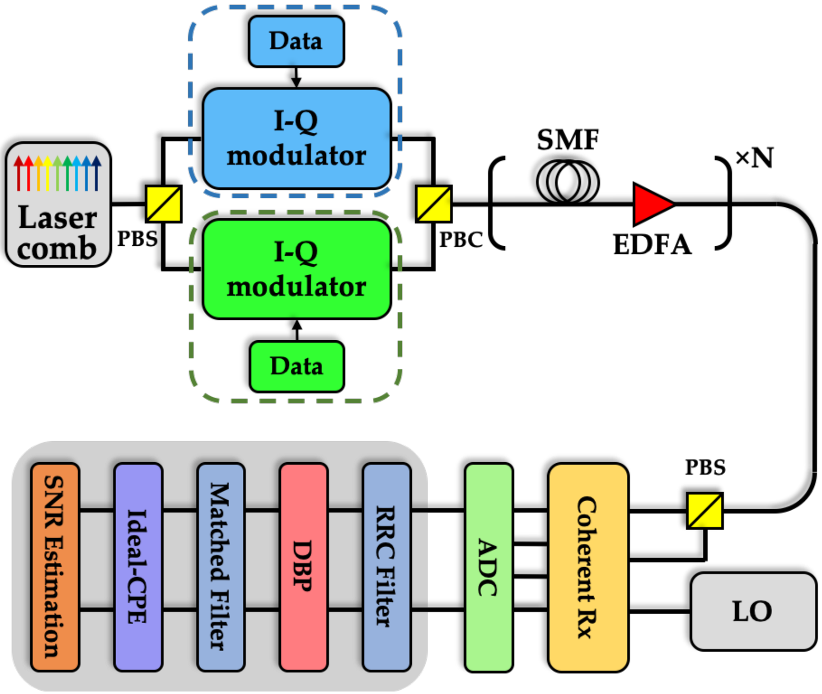

Figure 2. Transmission setup of the 9-channel 32-Gbaud DP-16QAM optical fiber communication system using digital back-propagation. I-Q: in-phase and quadrature, PBS: polarization beam splitter, PBC: polarization beam combiner, SMF: single-mode fiber, LO: local oscillator, Rx: receiver, ADC: analogue-to-digital convertor, SNR: signal-to-noise ratio.

Table 1. Parameters of the Transmission System

Symbol rate	32 Gbaud	**Number of channels**	9
Channel spacing	32 GHz	**Span length**	80 km
Central wavelength	1550 nm	**Attenuation coefficient (α)**	0.2 dB/km
Roll-off	0.1 %	**CD coefficient (D)**	17 ps/nm/km
EDFA noise figure	4.5 dB	**Nonlinear coefficient (γ)**	1.2 /W/km

Data sequences in WDM channels and two polarization states from the transmitter (Tx) are fully independent and random from each other. The Nyquist pulse shaping (NPS) is realized using a root-raised cosine (RRC) filter with a roll-off of 0.1%. The fiber span (SMF) is simulated based on the split-step Fourier solution of the dual-polarization Manakov equation with a logarithmic step size [12,19]. The erbium-doped fiber amplifier (EDFA) in each span is applied to compensate for the fiber loss. A span length of 80 km, commonly used in terrestrial systems, is applied, where the chromatic dispersion is fully mitigated using the EDC module in the DBP algorithm. The

DBP module is implemented employing the inverse split-step Fourier solution of the Manakov equation, and an RRC filter is applied to select the back-propagated signal bandwidth and to remove the unwanted amplified spontaneous emission (ASE) noise from the EDFA. The system performance is assessed by valuating the signal-to-noise ratio (SNR) in each transmission channel. Our numerical simulations neglected the laser phase noise, the frequency offsets from the transmitter and the local oscillator (LO) lasers, and the polarization mode dispersion. Other parameters of the coherent optical fiber communication system are listed in Table 1.

3. RESULTS AND DISCUSSIONS

The performance of SNR in each transmission channel in the 9-channel 32-Gbaud Nyquist-spaced DP-16QAM system is illustrated in Fig. 3, where the DBP is applied with two compensation bandwidths: a transmitted signal bandwidth of 288 GHz and a higher bandwidth accounting for the spectral broadening effect, 352GHz. Also, two transmission distances are considered: 800 km and 2000 km. It can be found that, the degradation in the DBP performance due to the negligence of the spectral broadening effect are significant in both scenarios (800 km and 2000 km), and the SNR penalties are higher for outer transmission channels. This demonstrates that there will be a truncation in the signal spectra if the DBP is applied with the transmitted signal bandwidth and the information loss due to the truncation becomes more significant for outer transmission channels [19-21]. It is shown in Fig. 3 that the SNR penalty is 0.3 dB in the central channel and 1.9 dB in outer channels for the 800 km system, and the SNR penalty becomes 0.2 dB in the central channel and 1.0 dB in outer channels for the 2000 km system. This provides us an insight that accounting for an additional compensation bandwidth will improve the performance of DBP considerably in the wideband optical communication systems, especially for outer transmission channels.

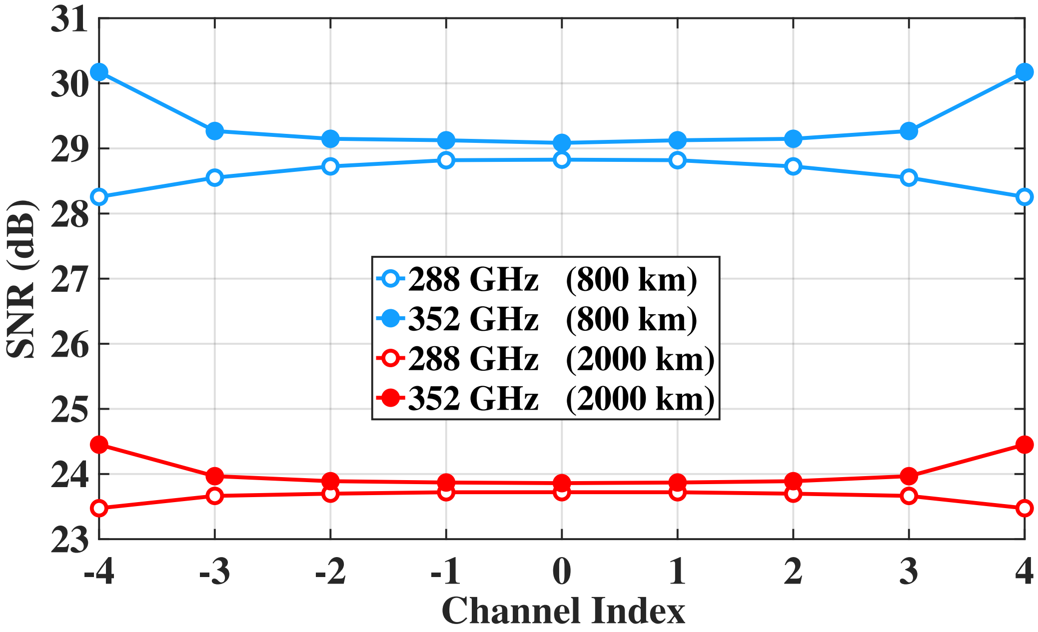

Figure 3. Performance of SNR in each channel for the 9-channel Nyquist-spaced DP-16QAM optical communication system, with transmission distances of 800 km and 2000 km. Two DBP bandwidths are considered: 288 GHz (transmitted bandwidth) and 352 GHz.

4. CONCLUSIONS

In this paper, the influence of the spectral broadening effect on the performance of digital back-propagation has been reviewed and discussed. It is found that the spectral broadening poses a significant effect on the performance of digital back-propagation in wideband WDM optical transmission systems. This impact will be more critical for outer transmission channels. For a 9-channel 32-Gbaud Nyquist-spaced system, an additional compensation bandwidth of 64 GHz can achieve the optimal performance of the full-band digital back-propagation. Our work demonstrated the significance of taking into account the spectral broadening effect in the optimal compensation of Kerr fiber nonlinearities.

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REFERENCES

[1] T. Kawanishi *et al.*: Wired and wireless links to bridge networks: seamlessly connecting radio and optical technologies for 5G networks, *IEEE Microwave Mag.*, vol. 19, pp. 102-111, Apr. 2018.

[2] R.J. Essiambre and R.W. Tkach: Capacity trends and limits of optical communication networks, *Proc. IEEE*, vol. 100, pp. 1035-1055, May 2012.

[3] T Xu *et al.*: High-order modulation formats, constellation design, and digital signal processing for high-speed transmission systems, in *Optical Fiber Telecommunications VII*, A. E. Willner, Ed., Academic Press, Oxford, 2020.

[4] H. Bülow *et al.*: Electronic dispersion compensation, *J. Lightwave Technol.*, vol. 26, pp. 158-167, Jan. 2008.

[5] E. Ip and J. M. Kahn: Digital equalization of chromatic dispersion and polarization mode dispersion, *J. Lightwave Technol.*, vol. 25, pp. 2033-2043, Aug. 2007.

[6] D.-S. Ly-Gagnon *et al.*: Coherent detection of optical quadrature phase-shift keying signals with carrier phase estimation, *J. Lightwave Technol.*, vol. 24, pp. 12-21, Jan. 2006.

[7] T. Xu *et al.*: Equalization enhanced phase noise in Nyquist-spaced superchannel transmission systems using multi-channel digital back-propagation," *Sci. Rep.*, vol.5, pp. 13990, Sep. 2015.

[8] M. Kuschnerov *et al.*: DSP for coherent single-carrier receivers, *J. Lightwave Technol.*, vol. 27, pp. 3614-3622, Aug. 2009.

[9] D. Semrau *et al.*: Achievable information rates estimates in optically amplified transmission systems using nonlinearity compensation and probabilistic shaping, *Opt. Lett.*, vol. 42, pp. 121-124, Jan. 2017.

[10] A.D. Ellis *et al.*: Performance limits in optical communications due to fiber nonlinearity, *Adv. Opt. Photon.*, vol. 9, pp. 429-503, Sep. 2017.

[11] G. Liga *et al.*: On the performance of multichannel digital backpropagation in high-capacity long-haul optical transmission, *Opt. Express*, vol. 22, pp. 30053-30062, Nov. 2014.

[12] T. Xu *et al.*: Modulation format dependence of digital nonlinearity compensation performance in optical fibre communication systems, *Opt. Express*, vol. 25, pp. 3311-3326, Feb. 2017.

[13] R. Maher *et al.*: Spectrally shaped DP-16QAM super-channel transmission with multi-channel digital back-propagation, *Sci. Rep.*, vol. 5, pp. 8214, Feb. 2015.

[14] D. Soh *et al.*: The effect of dispersion on spectral broadening of incoherent continuous-wave light in optical fibers, *Opt. Express*, vol. 18, pp. 22393-22405, Oct. 2010.

[15] S. V. Smirnov *et al.*: Optical spectral broadening and supercontinuum generation in telecom applications, *Opt. Fiber Technol.*, vol. 12, pp. 122-147, Apr. 2006.

[16] V. Mikhailov *et al.*: Limitation to WDM transmission distance due to cross-phase modulation induced spectral broadening in dispersion compensated standard fiber systems, *IEEE Photon. Technol. Lett.*, vol. 11, pp. 994-996, Aug. 1999.

[17] P. Suret and S. Randoux *et al.*: Influence of spectral broadening on steady characteristics of Raman fiber lasers: from experiments to questions about validity of usual models, *Opt. Commun.*, vol. 237, pp. 201-212, Jul. 2004.

[18] A. Mussot *et al.*: Spectral broadening of a partially coherent CW laser beam in single-mode optical fibers, *Opt. Express*, vol. 12, pp. 2838-2843, Jun. 2004.

[19] T. Xu *et al.*: Digital nonlinearity compensation in high-capacity optical communication systems considering signal spectral broadening effect, *Sci. Rep.*, vol. 7, pp. 12986, Oct. 2017.

[20] B. Karanov *et al.:* Digital nonlinearity compensation considering signal spectral broadening effects in dispersion-managed systems, in *Proc. OFC*, San Diego, California, United States, Mar. 2018, paper W2A.58.

[21] T. Xu *et al.*: Spectral broadening effects in optical communication networks: impact and security issue, in *Proc. ICAIT*, Stockholm, Sweden, Aug. 2018, paper A001-7.

[22] N.A. Shevchenko *et al.*: Modeling of nonlinearity-compensated optical communication systems considering second-order signal-noise interactions, *Opt. Lett.*, vol. 42, pp. 3351-3354, Sep. 2017.