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Spectral Broadening Effects in Optical Communication Networks: Impact and Security Issue

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Abstract: The impact of spectral broadening effects on the performance of nonlinear compensation applied to both modern dispersion-unmanaged and legacy dispersion-managed optical communication systems has been analysed and quantified. It is found that including the full broadened spectrum at the receiver enables a substantial improvement in the performance of nonlinear compensation.

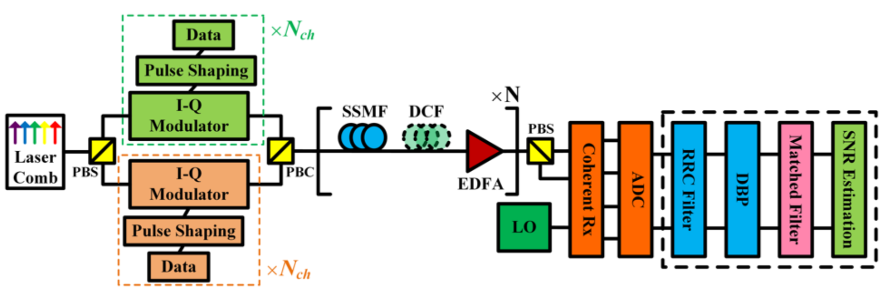
Key words: Optical communications; nonlinear fibre optics; spectral broadening; nonlinearity compensation

1. Introduction

Optical fibre networks form the major part of the current communication infrastructure and carry most of the generated digital data. The increasing demand for higher information rates has led to the development and application of higher-order modulation formats, denser wavelength division multiplexing (WDM) and more and more advanced digital signal processing (DSP). Nyquist-spaced transmission and DSP-based compensation have been combined for effectively enhancing the spectral efficiency and reach of optical communications. In dispersion-unmanaged (DUM) transmission systems where chromatic dispersion (CD) is compensated using DSP, Kerr fibre nonlinearities occur as the main capacity limit [1]. On the other hand, in installed submarine links in-line optical dispersion management is implemented by the periodic concatenation of standard single mode fibre (SSMF) and dispersion compensation fibre (DCF) spans. In such legacy systems nonlinear effects are even stronger than their dispersion-unmanaged counterparts due to the periodic phase matching [2]. In order to significantly increase the information rates in both types of optical transmission systems, the use of digital nonlinearity compensation (NLC) such as digital back-propagation (DBP) has to be considered [3,4].

During propagation, nonlinear interactions within the fibre medium lead to spectral broadening of the signal [5,6]. Thus, the received spectrum is not necessarily matched to the transmitted and the effect needs to be considered to achieve optimum detection and NLC. Spectral broadening effects (SBEs) have been investigated without using any NLC, where XPM-induced SBEs and their impact have been evaluated [6,7]. However, the impact of SBEs in transmission systems using NLC was reported for the first time in our previous work [5,8]. In this paper, the performance of full-field digital NLC is analysed considering SBEs in both DUM and dispersion-managed (DM) optical communication systems. It is found that accounting for SBEs is crucial for achieving the best performance of NLC and is more significant for outer channels in both systems. In addition, potential physical layer attack issue considering SBEs is also discussed.

2. Transmission Setup and Parameters



Wavelength	1550 nm (central)	
EDFA NF	4.5 dB	
	SSMF	**DCF**
Span length	80 km/50 km	9.5 km
Attenuation	0.2 dB/km	0.5 dB/km
Dispersion	17 ps/nm/km	-85 ps/nm/km
Nonlinearity	1.2 /W/km	5.67 /W/km

Figure 1. Setup for dispersion-unmanaged and dispersion-managed optical transmission systems using DBP and table of system parameters.

We investigated a representative setup of 5-channel 32-Gbaud DP-16QAM Nyquist-spaced coherent system as shown in Fig. 1. The fibres in the link are simulated using a split-step Fourier method of the Manakov equation with a logarithmic step size. The DBP is realised using the inverse solution of the Manakov equation with an ideal RRC filter applied to select the desired back-propagated bandwidth. The EDFA in each span is included to fully compensate for the fibre loss. In the DUM transmission scheme, a span length of 80 km is employed, which is a typical value for long-haul terrestrial optical links, and the CD is fully compensated using the dispersion compensation module in DBP. In the DM scheme, a 50 km SSMF span, a common length for deployed submarine systems, and 9.5 km DCF fibre was simulated over multi-span transmission with a 5% under-compensation dispersion map [9]. Other parameters of transmission systems are detailed in

Table 1. This study assumes 2000 km of SSMF, net of DCF in the transmission, which is 25 spans for DUM case and 40 spans for DM case. The phase noise from transmitter and LO lasers, their frequency offset and fibre PMD are all neglected.

3. Results and Discussions

In Fig. 2, the SNR across different channels is shown for different compensation bandwidths in MC-DBP. For a compensation bandwidth of 160 GHz (the same as the transmitted signal bandwidth), an SNR penalty in MC-DBP for all channels was observed for both DUM and DM systems. In both cases a 176-GHz was applied for realising the best DBP performance for all channels. It is shown that, the degradation in DBP performance due to SBEs is higher for outer channels. Because the DBP using the transmitted signal bandwidth will lead to a truncation of the nonlinearly-broadened spectra and the information loss due to the truncation is more serious for the outer channels (closer to the edge of signal spectra) [5]. Figure 2 shows that the SNR penalty is 0.3 dB in central channel and 1.5 dB in outer channels for the DUM system, and the penalty is 0.2 dB in central channel and 0.9 dB in outer channels for the DM system. The results suggest that the inclusion of a constant additional DBP bandwidth (~16 GHz) ensures considerably improved DBP performance in both DUM and DM optical communication systems, which, in this case, is an excess bandwidth of 10%.

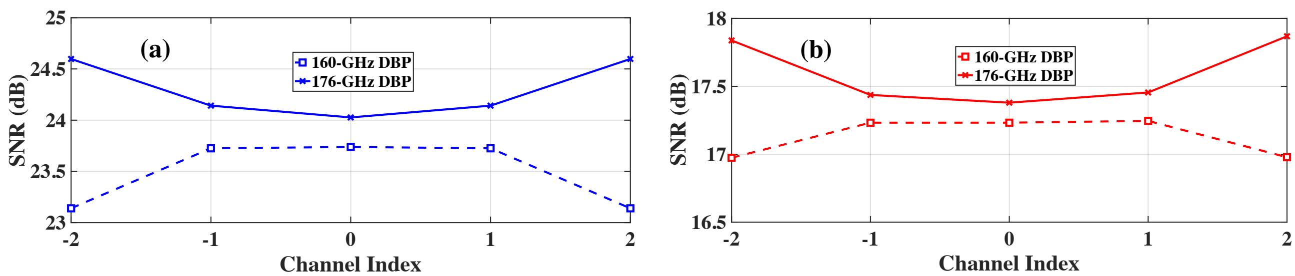


Figure 2. SNR performance versus channel index for systems using MC-DBP of 160 GHz (transmitted bandwidth) and 176 GHz (a) dispersion-unmanaged system, (b) dispersion-managed system. Optimum launch powers have been applied.

4. Physical Layer Security Issue

SBEs have also to be considered in physical-layer attacks of optical networks such as high-power jamming attacks, which will happen when an optical signal of excessive power on a legitimate channel or on a wavelength outside the signal window is inserted. Due to increased SBEs in fibres, such a high-power signal can significantly distort co-propagating user channels. In modern optical networks, ROADMs with variable optical attenuators (VOAs) are deployed to regulate the output power of transiting signals, so that a jamming signal would be attenuated at the first downstream node. However, it would still cause significant SBE-induced crosstalk to co-propagating signals on the link where it was inserted.

5. Conclusion

The impact of SBEs on the performance of NLC in dispersion-unmanaged and dispersion-managed links was investigated. For both systems, SBEs have a strong impact on nonlinear compensation performance. Remarkably, both sets of results indicate that a relatively small, and constant, additional DBP bandwidth (~16 GHz in our study) includes the spectral components of the signal, and its consideration optimises the compensation. For the 5-channel system considered in both DUM and DM systems, the additional DBP bandwidth required was 10%. Therefore, our study quantifies the importance of the signal spectral broadening for optimum compensation of deterministic nonlinear interactions in such systems.

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