Digital Nonlinearity Compensation Considering Signal Spectral Broadening Effects in Dispersion-managed Systems

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Abstract: The impact of spectral broadening on the performance of nonlinear compensation applied to legacy submarine dispersion-managed links is studied. An additional 2.2 dB SNR improvement at optimum launch power is achieved by optimizing the compensated bandwidth.
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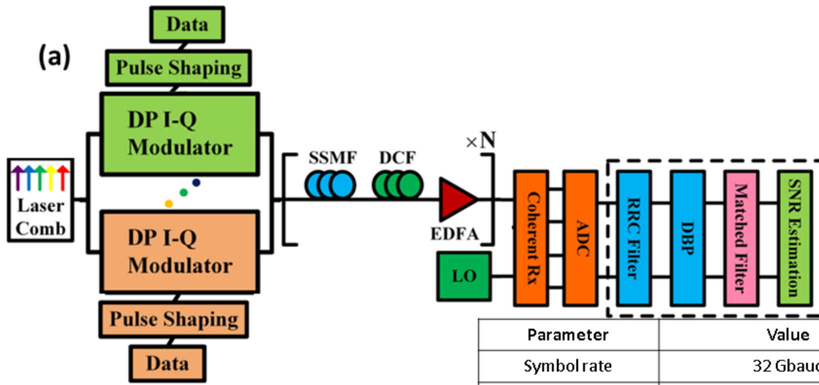
1. Introduction

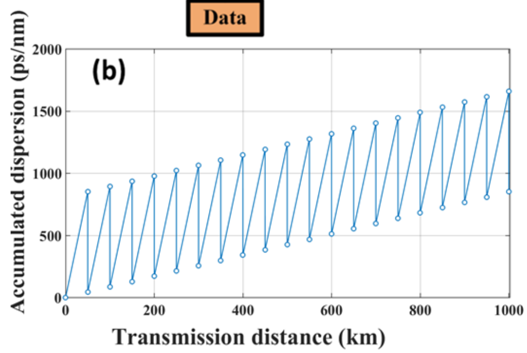
A significant improvement in optical communication spectral efficiency is required to meet ever-increasing information rate demands. In modern systems this is achieved through a combination of Nyquist-spaced wavelength division multiplexing (WDM) and coherent reception of transmitted signals; the latter enabling the use of high order modulation formats accompanied by advanced digital signal processing (DSP) to mitigate signal distortions [1]. Capacity enhancement is necessary in many installed long-haul submarine links where in-line optical dispersion management (DM) is implemented by the periodic concatenation of spans of fibers with inverse dispersion parameters [2]. Although practical schemes undercompensate dispersion in each span to reduce phase matching and thus mitigate nonlinear interactions, nonlinear effects in these systems are still significantly stronger than their dispersion-unmanaged counterparts. Thus, to significantly increase the achievable information rate in such legacy links, one must consider the use of digital nonlinearity compensation [3,4]. For DM links, this is feasible because the periodic dispersion map can be exploited to facilitate a significant computational complexity reduction for algorithms such as digital backpropagation (DBP) [3-5].

Nonlinear optical fiber propagation leads to spectral broadening of the signal [6-8]. For dispersion-unmanaged systems it was shown that consideration of the broadening is important for optimum compensation of fiber nonlinearities [9]. The broadening effect strongly depends on fiber dispersion [7]. For DM links, considerable degradations in transmission distance and bit-error-rate performance due to spectral broadening have been reported [8]. Even when the optical receiver and signal processing devices match the transmitted signal bandwidth, truncation of received signal spectral components may still occur due to the broadening effect. Yet, no investigation has been conducted on the impact of this truncation on nonlinear compensation performance in DM systems where the broadening effect is significantly stronger compared to the unmanaged systems. In this paper, the performance of full-field digital nonlinearity compensation is examined, specifically considering the spectral broadening effects in DM WDM systems. It is shown that backpropagation of the full broadened spectrum significantly increases the SNR gains at optimum launch powers and, thus, allows an improved compensation of signal-signal nonlinear effects.

2. Transmission Parameters and Simulation Setup

To numerically investigate the impact of spectral broadening on nonlinearity compensation, both a single-channel and a 5-channel 32 GBaud Nyquist-spaced WDM transmission system was simulated over multi-span cascades of standard single mode (SSMF) and dispersion compensating (DCF) fibers. The system schematic is illustrated in Fig. 1(a) where the fibers' parameters are also listed in the table inset. In [9], it was verified that spectral broadening is modulation format independent and thus, for indicative purposes, the following results are generated using DP-16QAM. A practical submarine system with 50 km SSMF span lengths was investigated, using a representative dispersion map, shown in Fig. 1(b), corresponding to 5% undercompensation (adopted from [4]). The study assumes 20 and 40 spans (corresponding to 1000 and 2000 km of SSMF, net of DCF). The split-step Fourier solution of the Manakov equation with a logarithmic step-size distribution was used to simulate the fiber propagation [9]. The EDFAs following each span fully compensate for the fiber loss. The DBP was realized using the inverse solution of the Manakov equation with an ideal RRC filter applied to select the desired backpropagated bandwidth. The number of steps per span was kept equal for the forward and backward propagation to achieve optimal compensation performance. The phase noise from transmitter and local oscillator lasers, their frequency offset and fiber polarization mode dispersion are neglected.





Parameter	Value	
Symbol rate	32 Gbaud	
Channel spacing	32.032 GHz	
Wavelength	1550 nm (central)	
Channel number	1 and 5	
RRC filter roll-off	0.1%	
EDFA NF	4.5 dB	
Fibre Parameter	**SSMF**	**DCF**
Span length	50 km	9.5 km
Attenuation	0.2 dB/km	0.5 dB/km
Dispersion	17 ps/nm/km	-85 ps/nm/km
Nonlinear coefficient	1.2 /W/km	5.67 /W/km

Fig. 1. Multi-channel DM transmission system simulation using DBP (a) LO: local oscillator, ADC: analogue-to-digital converter, N: number of spans. (b) Dispersion map. Inset table: system parameters.

3. Results and Discussion

Figure 2(a), (c) show the received signal spectra for single-channel and 5-channel (indexed -2,-1,0,1,2) transmission for 1000 and 2000 km transmission distances. The launched optical power per channel in both cases is 4 dBm which is the optimum power for the 5-channel system with full-field DBP. We can observe that the received signal contains an additional spectral band outside of the transmitted spectrum. The impact of this spectral broadening is emphasized in Fig. 2(b), (d) where the optical launch power versus SNR is shown for different backpropagated bandwidths in the examined systems. For the single-channel case (Fig. 2(b)) after 1000 km 32-GHz (transmitted bandwidth) DBP gives an SNR of 21.8 dB at optimum launch power, whereas this value increases to 24.7 and 24.8 dB, when 48- and 64-GHz DBP is applied, respectively. Similarly, for the 2000 km transmission distance, the optimum SNR is enhanced from 17.4 to 19.2 dB when the DBP bandwidth increases from 32 to 48 GHz. Since the outer channels in WDM systems are more affected by spectral truncation [9], Fig. 2(d) shows the SNR versus launch power for the outer channel (indexed -2) in the 5-channel transmission. By increasing the backpropagated bandwidth from 160 GHz to 176 GHz, an SNR improvement of 1.5 and 0.9 dB is observed at 1000 and 2000 km, respectively. Fig. 2(e) shows the SNR for each of the 5 channels for different DBP bandwidths. The launched power is the optimum for the central channel in the 160-GHz and 172-GHz cases. Including the spectral broadening in the DBP gives a more significant improvement to the outer channels compared to the central channel; 2.2 dB compared to 0.3 dB at 1000 km transmission distance.

The results suggest that the inclusion of a constant additional DBP bandwidth (~16 GHz) for all transmitted signal bandwidths ensures considerably improved DBP performance, which, in this case, is an excess bandwidth of just 10%. This is in stark contrast to previous analyses of DBP for DM systems, which, due to the use of low symbol rate signals, stated an optimum required oversampling bandwidth of between 300% and 400% [5].

We verified that these results are consistent with the values obtained by the method adopted in [9], where the received signal bandwidth is defined as the bandwidth amounting to 99.99% of the transmitted signal power. Thus, the full signal spectrum is captured and processed at the receiver to achieve optimum nonlinearity compensation. It is important to note that the impact of spectral broadening on nonlinearity compensation in DM links is considerable even at low optimum launch powers. This contrasts with dispersion-unmanaged systems where similar SNR improvement was observed at much higher launch powers. This is due to the enhanced four wave mixing as an effect of the dispersion map's periodic structure, which gives rise to the nonlinear interactions. Furthermore, Fig. 2(c), (d) and (e) show that the impact of spectral broadening on DBP performance is stronger at 1000 km and decreases at 2000 km. At shorter distances where the contribution of amplified spontaneous emission noise and nonlinear distortions are smaller, truncation of the signal spectrum before nonlinearity compensation results in higher SNR degradation. As the former effects become more dominant when distance is increased, the impact of spectral broadening on DBP performance reduces.

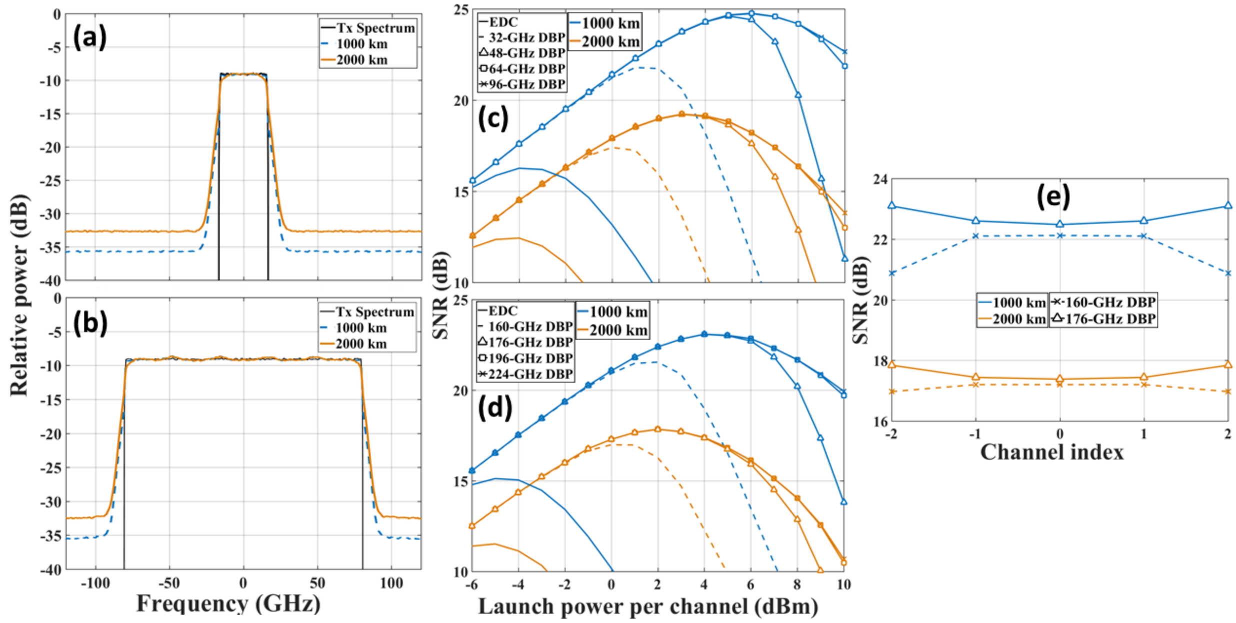


Fig. 2. Spectral broadening effect (4 dBm/ch) for (a) single-channel (32 GHz) and (c) 5-channel (160 GHz) transmission and (b) its impact on the SNR as a function of launch power for single-channel and (d) the outermost of 5-channel systems using DBP. (e) SNR versus channel index in 5-channel system for different DBP bandwidths. Power (optimum for central channel) is 3 dBm (160-GHz DBP) and 4 dBm (176-GHz DBP).

4. Conclusions

The impact of signal spectral broadening on the performance of nonlinearity compensation in DM links was investigated for single-channel and WDM transmission. As with dispersion unmanaged systems, the broadening effect in DM links has a strong impact on nonlinear compensation performance, albeit at lower optimum launch powers. Remarkably, the results for both single- and multi-channel systems 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 optimizes the compensation. Crucially, for the 5-channel system considered in this work, the additional DBP bandwidth required was just 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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