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Digital back-propagation for nonlinearity mitigation in distributed Raman amplified links

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Abstract: The performance of digital back-propagation (DBP) for distributed Raman amplified optical communication systems is evaluated through analytical models and numerical simulations, and is compared with conventional lumped amplifier solutions, such as EDFA. The complexity of the DBP algorithm including the characteristic signal power profile of distributed Raman amplifiers is assessed. The use of full-field DBP in distributed Raman amplified systems leads to 1.3 dB additional gain with respect to systems employing lumped amplification, at the cost of only a 25% increase in complexity.

OCIS codes: (060.2330) Fiber optics communications; (190.4370) Nonlinear optics, fibers; (290.5910) Scattering, stimulated Raman.

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1. Introduction

Achievable rates in optical fibre communication systems are currently limited by a variety of factors. Among them, two of the main limitations are (i) signal-to-noise ratio (SNR) degradation due to nonlinear distortions introduced by the Kerr effect, and (ii) the optical amplifier bandwidth limiting the possible number of wavelength channels. Raman amplification has become a key technology to continue the development of long-haul high-capacity systems due to the possibility to expand the amplifier bandwidth beyond the conventional erbium-doped fibre amplifier (EDFA) window, and the offer of an improved amplified spontaneous emitted (ASE) noise performance in distributed amplification regime [1]. However, compared to lumped amplifier solutions, the use of distributed amplification leads to increased non-linear distortion due to a higher average signal power across the fibre span. Numerous solutions to mitigate nonlinear impairments arising from the Kerr effect have been investigated, ranging from optical to digital techniques, with both types experimentally demonstrated to enhance the reach of transmission systems [2, 3]. Digital back-propagation (DBP) is a receiver-based digital technique proposed to jointly compensate chromatic dispersion and nonlinear effects by solving an inverse propagation equation [4]. Recently, the use of full-field nonlinearity compensation for ultra-wide bandwidth optical communication systems based on distributed Raman amplification was theoretically studied, showing impressive benefits when combined with high order modulation formats [5]. However, the use of DBP on Raman amplified systems has received only limited attention, with few experimental demonstrations showing gains of approximately 1 dB in the system quality factor [6, 7], or allowing an increase in transmission distance [8, 9]. While the benefits and challenges of DBP in EDFA-based optical systems are well known, a complete study of non-ideal, multi-span, distributed Raman systems has not been carried out to date. The trade-offs between the reduced ASE noise contributions and the higher amount of nonlinear effects, and their impact on achievable gains and algorithm complexity when performing DBP still need to be studied for distributed Raman amplified links.

In this work we investigate the performance of digital back-propagation for multi-span, backward pumped Raman amplified transmission systems. Firstly, theoretical benefits of the use of DBP are analysed using the Gaussian-Noise (GN) model for EDFA and Raman systems. Secondly, in order to assess the performance predicted by the model and study the algorithm complexity simulations were carried out for a 5 channel, Nyquist-spaced polarization division multiplexed 16-ary quadrature amplitude modulation (PDM-16QAM) system at a symbol rate of 32 GBd. Finally, the results are extended for a fully loaded C-band system of approximately 5 THz of bandwidth and the gains offered by DBP in SNR and achievable rates are studied.

2. Analytical model

In order to study the performance of distributed Raman and EDFA-based systems, the GN-model was utilized [10]. The GN-model allows for the estimation of the nonlinear interference (NLI) or distortions present in an optical communication system, and exhibits good accuracy for highly dispersive long-haul links. One of the key assumptions in the model is that the signal constellation is Gaussian. A number of models have been proposed that remove this assumption and take the modulation dependence into account [11, 12]. However, by accounting for modulation dependence the computational complexity increases dramatically due to the need of additional integrations to be carried out, especially for non-ideal distributed Raman amplification and large optical bandwidths. For this reason the modulation format dependence is neglected in this work in order to ensure that the computational effort is manageable.

The NLI is considered to be additive, Gaussian and thus the signal-to-noise ratio (SNR) at the receiver is given by

$$\text{SNR} = \frac{P}{P_{\text{ASE}} + P_{s-s} + P_{s-n}}, \tag{1}$$

with signal launch power P, ASE noise power P_{ASE}, NLI noise power resulting from signal-signal interactions P_{s-s} and NLI noise power resulting from signal-noise interactions P_{s-n}. Equation (1) can be used to predict the SNR of an optical communication system. If the system only compensates electronically for chromatic dispersion at the receiver (EDC), then, the term P_{s-s} is much larger than P_{s-n}, therefore, P_{s-n} can be neglected. When full-field DBP (FF-DBP) is carried out the term P_{s-s} is neglected due to the compensation of the signal-signal interactions. It is assumed that the NLI coefficients for signal-signal interactions are approximately equal to the ones of signal-noise interactions. The NLI terms are computed similarly to [13]

$$P_{s-s} = N_s^{1+\epsilon} \eta P^3, \tag{2}$$

$$P_{s-n} \approx 3 P_{\text{ASE}} \xi \eta P^2, \tag{3}$$

with

$$\xi \approx \sum_{k=1}^{N_s} k^{1+\epsilon}, \tag{4}$$

with NLI coefficient η, number of spans N_s and coherence factor ϵ, responsible for coherent noise accumulation along the link. ϵ is calculated according to [10]. The NLI coefficient for the central channel is computed as

$$\eta = \frac{16\gamma^2}{27 R_s^2} \int \int_{-\frac{B}{2}}^{\frac{B}{2}} \Pi\left(\frac{f_1 + f_2}{B}\right) \rho(f_1, f_2) df_1 df_2, \tag{5}$$

with total bandwidth $B = N_{ch} \cdot R_s$, where N_{ch} represents the number of channels, R_s the symbol rate, and $\Pi(x)$ denotes the rectangular function. The function $\rho(f_1, f_2)$ in Eq. (5) depends on the signal power profile along the span, and therefore, on the used amplifier scheme. The signal power profile of distributed Raman amplifiers is defined by the well-known set of coupled differential equations [1, 14]

$$\frac{dP_s}{dz} = -\alpha_s P_s + C_R P_p P_s, \tag{6}$$

$$-\frac{dP_p}{dz} = -\alpha_p P_p + \left(\frac{\lambda_s}{\lambda_p}\right) C_R P_p P_s, \tag{7}$$

where P_s and P_p represent optical power from signal and pump respectively, C_R corresponds to the Raman gain coefficient normalised to the effective area of the fibre, and α_s and α_p are the attenuation coefficients at the signal and pump wavelength respectively. For lumped-like amplification (e.g. EDFA) and non-ideal backward-pumped Raman amplification, neglecting pump to signal depletion, the functions $\rho(f_1, f_2)$ are then given by

$$\rho_{\text{EDFA}} = \left| \frac{1 - e^{\alpha_s L_s} e^{j4\pi^2 f_1 f_2 \beta_2 L_s}}{\alpha_s - j4\pi^2 f_1 f_2 \beta_2 L_s} \right|^2, \tag{8}$$

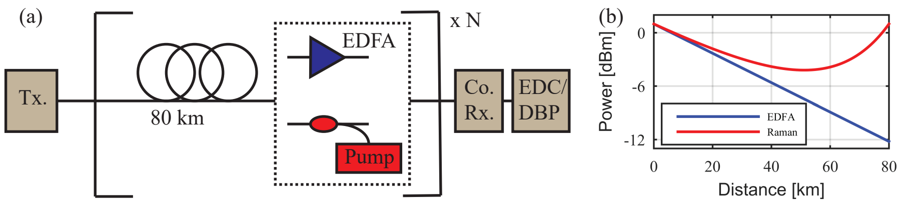

Fig. 1. (a) Schematics of the simulation system. (b) Signal power profiles used for Raman (red) and EDFA systems (blue).

$$\rho_{\text{Raman}} = \left| e^{-\frac{C_R P_{p0}}{\alpha_p}} \int_0^{L_s} e^{-\alpha_s z} e^{\frac{C_R P_{p0}}{\alpha_p} e^{\alpha_p z}} e^{j4\pi^2 f_1 f_2 \beta_2 z} dz \right|^2 , \tag{9}$$

with the span length L_s, the group velocity dispersion parameter β_2 and the initial pump power P_{p0}. Equations (1)-(9) were used to calculate the SNR at optimum signal launch power, the power at which the maximum SNR is found in the system. Expressions for the maximum SNR can be obtained for both cases. For the scope of this paper, and for better theoretical understanding, we express the gain of FF-DBP relative to EDC only as the ratio between both SNRs and obtain:

$$\frac{SNR_{\text{FF-DBP}}}{SNR_{\text{EDC}}} = \frac{3^{\frac{1}{2}} N_s^{\frac{\epsilon}{3}+\frac{1}{2}}}{2^{\frac{5}{3}} \xi^{\frac{1}{2}} \eta^{\frac{1}{6}} P_{\text{ASE}}^{\frac{1}{3}}} \tag{10}$$

For a fixed number of spans, the logarithmic scaling of Eq. (10) dependant on the NLI coefficient and the ASE noise is given approximately by:

$$\Delta \frac{SNR_{\text{FF-DBP}}}{SNR_{\text{EDC}}} [\text{dB}] \approx -\frac{1}{6} \eta [\text{dB}] - \frac{1}{3} P_{ASE} [\text{dB}] \tag{11}$$

The GN-model offers the possibility to study different back-propagation bandwidths by redefining Eq. (2)as:

$$P_{s-s} = (N_s^{1+\epsilon_c} \eta_c - N_s^{1+\epsilon_{DBP}} \eta_{DBP}) P^3, \tag{12}$$

where η_c is the NLI coefficient and ϵ_c the coherence factor of the total transmitted optical bandwidth B. Additionally, η_{DBP} is the NLI coefficient of the back-propagated signals with coherence factor ϵ_{DBP} and bandwidth B_{DBP}.

3. Simulation system

In order to assess the system performance predicted by the model described in the previous Section, numerical simulations were carried out, with the simulated system shown in Fig. 1(a).

Table 1. Fibre parameters

Parameter	Value
Attenuation coefficient @ 1550 nm (α_s)	0.160 [dB]
Attenuation coefficient @ 1450 nm (α_p)	0.20 [dB]
Dispersion parameter (D)	16.2 [ps/(nm.km)]
Nonlinear coefficient (γ)	1.2 [$W^{-1}km^{-1}$]
PMD	0 [ps/$\sqrt{km}$]
Span length (L_s)	80 [km]
Raman gain coefficient (C_R)	0.2 [1/W/km]

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An ideal optical transmitter was assumed to generate 5 Nyquist-spaced polarization division multiplexed 16-ary quadrature amplitude modulated (PDM-16QAM) channels at a symbol rate of 32 GBd. The generated signal was sampled at 4 samples per symbol to include nonlinear induced pulse broadening effects, and subsequently Nyquist shaped using a root raised cosine (RRC) filter with 0.1% roll-off factor. Transmission over the 80 km optical fibre span was simulated by numerically solving the Manakov equation using the split step Fourier method (SSFM) with a step size of 100 m to ensure sufficient accuracy. The signal was optically amplified using one of the following methods: (i) an EDFA after each span with noise figure of 4.5 dB; (ii) backwardly-pumped, distributed Raman amplifier. The signal power profile used for the simulation of the distributed amplifier is described by Eqs. (6) and (7). Backward-pumping configuration was selected because it offers reduced relative intensity noise (RIN) transfer and polarization-dependant gain compared to other pumping schemes [14], such as forward or bidirectional-pumping. In both cases the optical amplifiers were set to compensate the loss of the span exactly, and 480 mW was used as the Raman pump power for this purpose. The receiver was designed to carry out either EDC in the frequency domain or FF-DBP. The signal power profiles of both amplifier schemes, which can be seen in Fig. 1(b), were included in the DBP algorithm. This was required because each signal power profile leads to different NLI during transmission, and in order to properly compensate signal-signal nonlinear interactions the power profile used for back-propagation needs to match that used in transmission. After DBP, a filter matched to the pulse shape was applied, and carrier phase estimation was performed. Finally, SNR was ideally estimated as the ratio between the variance of the transmitted symbols $E[|X|^2]$ and the variance of the noise σ^2, where $\sigma^2 = E[|X - Y|^2]$ and Y represents the received symbols after digital signal processing as detailed in [15]. Additional fibre parameters can be found in Table 1.

4. Results and discussion

Two different system scenarios were analysed in this work. The first corresponds to the transmission of a 5PDM-16QAM super-channel and the performance of both amplification schemes is assessed at different distances through simulations and the GN-model. The second scenario extends the results to a fully loaded C-band system of practical interest using the GN-model.

4.1. Super-channel system

The performance of the systems were analysed for different distances, ranging from 2000 km up to 8000 km, and signal launch powers from -15 to 10 dBm per channel. SNR was used as the performance metric to evaluate the performance of both systems, with the results plotted in Fig. 2. The SNR for both amplification schemes at 2000 km as a function of signal power is shown in Fig 2(a). It can be seen that the improved ASE noise performance from the distributed Raman amplifier offers a better performance in the linear transmission regime, that is translated into 2.9 dB higher SNR at optimum launch power than EDFA when only EDC is carried out at the receiver. Furthermore, a more severe degradation of the SNR in the nonlinear regime is clearly visible when Raman amplifiers are used, due to the higher signal power profile in the transmission fibre, as seen in Fig. 1(b). The use of FF-DBP at the receiver allows deterministic nonlinear distortions experienced during propagation to be compensated, enhancing the SNR. At 2000 km in the EDFA system, back-propagating all 5 transmitted channels results in an increase in the maximum SNR of some 8.9 dB compared to EDC only. However, when FF-DBP is applied in the Raman amplified system, it leads to an increase of 10.2 dB compared to the EDC only case. Equation (11) offers insight on the parameters of the optical system that influence the achievable gain when applying FF-DBP. A higher NLI coefficient leads to a decrease in the gain of FF-DBP. Likewise, larger ASE noise contribution from the amplification process will have the same effect. Backward-pumped Raman amplification exhibits a higher nonlinear distortion coefficient due

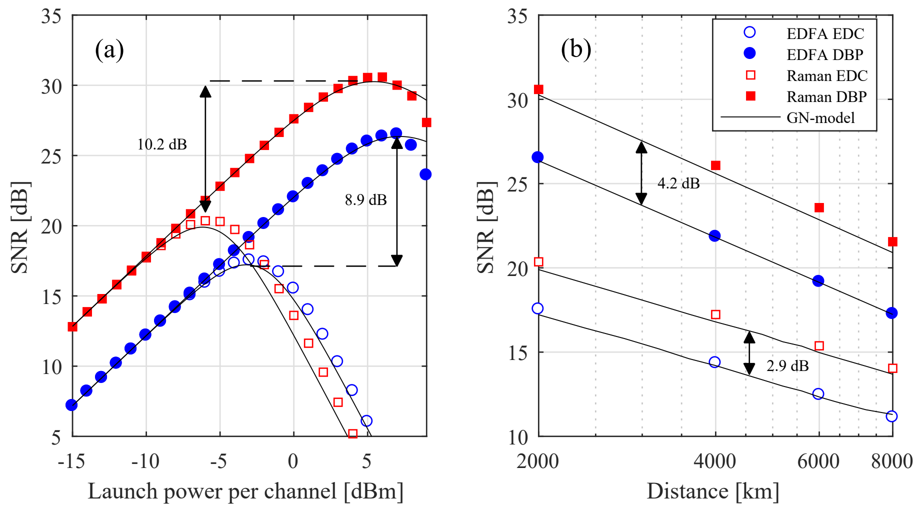

Fig. 2. Benefits of DBP for Raman amplified systems for the super-channel system. (a) Received SNR as a function of signal launch power at 2000 km, (b) received SNR as a function of distance at optimum launch power. Circles and squares represent EDFA and Raman simulated systems respectively. Open markers correspond to EDC only and solid markers correspond to the use of DBP. Solid lines represent GN model predictions.

to a higher average power along a span, however, the improved ASE noise performance leads to a larger FF-DBP gain in Raman systems compared to the gain in EDFA systems. For the analysed system, the use of distributed Raman amplification together with FF-DBP exhibits a gain 1.3 dB higher relative to the use of EDFA. Additionally, it is worth noting a good agreement between the simulations and the GN-model for both amplification schemes, at least up to optimal launch power when EDC and DBP is applied at the receiver, as seen if Fig. 2(a). In Fig. 2(b) the SNR at optimal launch power is plotted for different transmission distances. In the absence of nonlinearity compensation, the use of distributed Raman amplification always offers an improved performance than EDFA, with 2.9 dB higher SNR at optimal signal launch power. This benefit is enhanced by the use of FF-DBP, with an improvement in SNR (up to 4.2 dB) at all evaluated distances consistent with the theory described in Eq. (11). The observed FF-DBP gains for the EDFA system at 2000, 4000, 6000 and 8000 km were 8.9, 7.5, 6.7, 6.1 dB respectively. Alternatively, the FF-DBP gains observed in the Raman systems were 10.2, 8.8, 8.2, and 7.5 dB for the same distances. This means that the 1.3 dB increase in gain presented by the Raman based system is maintained even at longer distances, where DBP gains are decreased due to the interaction between ASE noise and nonlinear distortions.

The DBP algorithm needs to properly match the power profile from the signal in order to compensate for deterministic nonlinear effects that take place during transmission, therefore the use of backward-pumped distributed Raman amplification, with a more complex signal power profile, leads to an increase in the number of steps per span required to obtain the maximum gain from DBP. For the studied systems the algorithm complexity was evaluated at 2000 km using the number of steps per span required to obtain the maximum gain when applying FF-DBP. The signal power profiles used are shown in Fig. 1(b), and, in order to carry out a fair comparison, no simplifications (e.g. log step for EDFA) were used in the DBP algorithm to reduce the number of steps per span on either amplification schemes. To assess the DBP complexity, the number of equally distanced steps per span was swept from 1 to 400 in increments of 40 for both amplifiers. Figure 3 shows the gain in SNR after DBP is carried out as a function of the number of steps per span used in the algorithm. For the EDFA system a total number of 160 steps

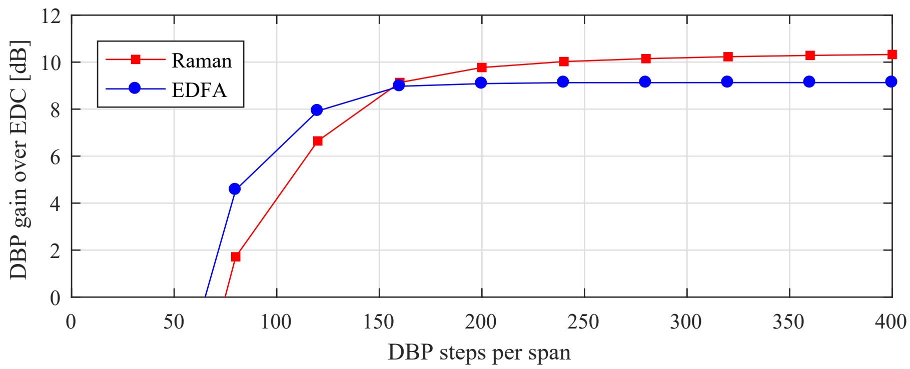

Fig. 3. Gain obtained from performing FF-DBP using different steps per span.

per span were required to achieve the maximum gain from DBP, showing good agreement with previous studies in this area [16]. For the Raman-amplified system however, 200 steps per span were required to obtain a gain larger EDFA. This represents a 25% increase in the required number of steps to achieve the maximum gain from DBP. During transmission the signal experiences power dependant phase shifts from nonlinear interactions. In the presence of distributed amplification the nonlinear phase shifts are distributed along the fibre span as the signal power does not experience large power losses during propagation. EDFA-based systems, on the other hand, experience the majority of the nonlinear effects on the first kilometres of the fibre span, where the signal power is highest. For this reason, the signal power profile from distributed Raman amplifiers is responsible for the complexity increase in the DBP algorithm and a larger number of steps is required to fully compensate the impairments experienced during transmission. Additionally, the use of an inadequate number of steps for back-propagation leads to an incomplete compensation of the nonlinear distortions, leading to smaller gains than expected or even detrimental effects due to back-propagation ineffectively compensating the transmission effects.

4.2. Fully loaded C-band system

Optical communication systems seek to increase system throughput by utilizing all the available bandwidth with signals using multiplexing techniques. This leads to increased NLI over different channels and the ability of performing FF-DBP being eventually limited by the receiver bandwidth. The study of large bandwidth systems requires complex computational simulations or experimental demonstrations, each one of them with well known limitations, such as the availability of computational resources for simulations or implementation penalties that limit the gains expected from nonlinearity compensation. Analytical models however, offer the possibility of studying a variety of systems, and good agreement with simulations and experimental demonstrations has been previously shown [10]. In order to study the benefits of DBP for both amplification schemes in a fully loaded environment, a system with a total of 155 wavelength division multiplexed channels, occupying the entire C-band ($\approx$ 4.96 THz), was analysed using the GN-model. All other system parameters presented in section 3 remain the same. Equation (12) was used to study the benefits of back-propagating a different number of channels for a distance of 2000 km. The number of back-propagated channels was varied from 0 (EDC-only) to 155 (FF-DBP) and the SNR values at the respective optimum signal launch power were calculated. The calculated SNR for both systems as a function of the back-propagated bandwidth are shown in Fig. 4(a). The maximum SNR of the EDFA system using EDC was found to be 16.2 dB at a signal power of -6 dBm per channel, while the Raman case, SNR was 19.1 dB at -9 dBm per

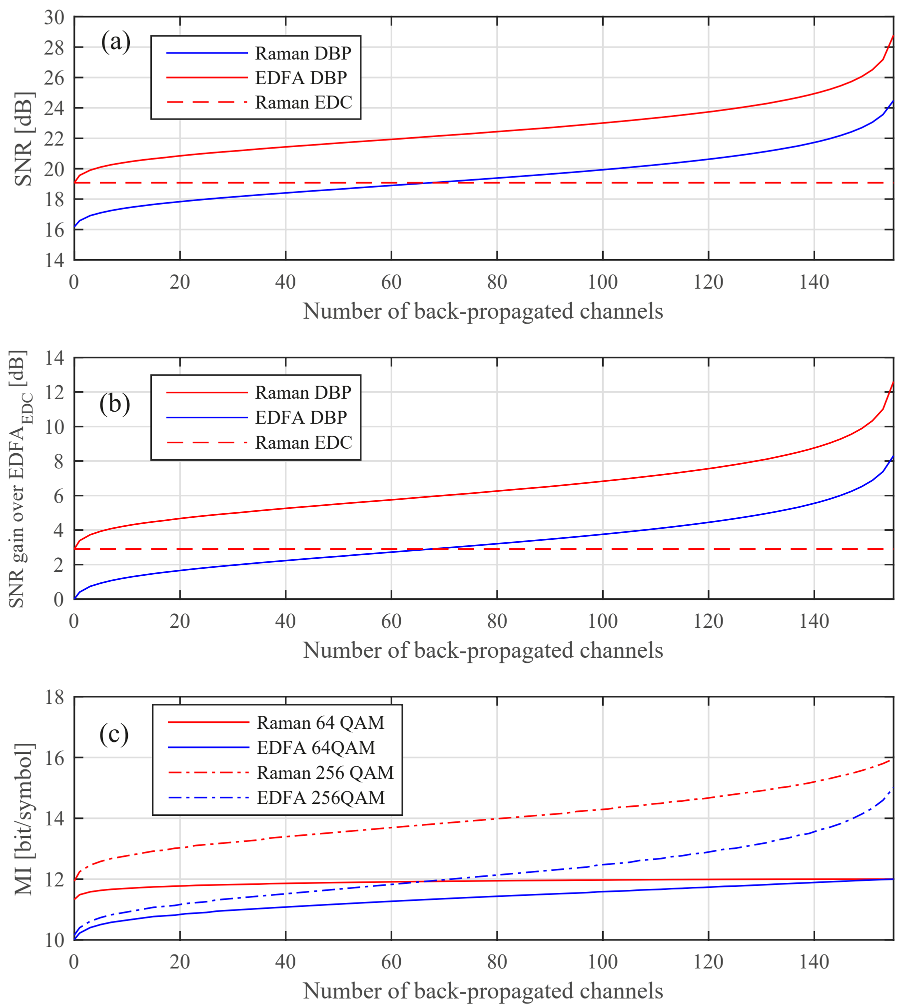

Fig. 4. (a) Calculated SNR, (b) SNR gain over the EDFA EDC performance and (c) mutual information (MI) as a function of back-propagated bandwidth for C-band loaded Raman and EDFA amplified systems. (a) Solid lines represent the SNR after DBP, dashed line represents the EDC performance of the Raman amplified system. (b) Solid lines represent the SNR gains over EDFA using EDC and dashed line represents the EDC performance of the Raman amplified system. (c) Solid lines and dash-dot lines represent the achievable rates after DBP for EDFA and Raman systems using 64- and 256QAM respectively.

channel. The obtained DBP gains over the performance of the EDFA system using EDC, are shown in Fig. 4(b).

In the absence of DBP, distributed Raman amplification exhibited 2.9 dB higher SNR compared to the EDFA, showing similar gain in performance as the super-channel system. As the number of back-propagated channels increases, the NLI arising from signal-signal interactions is mitigated increasing the gain experienced in both amplification schemes. When approaching FF-DBP, the term P_{s-s} presented in Eq. 12 tends to zero, therefore the gain experienced by the system will be limited by the interaction between nonlinear effects and ASE noise, as shown in Eq. (11). The result of compensating all the deterministic nonlinear effects in the Raman amplified system yields a 4.4 dB improvement compared to the use of EDFA. In general, the use of DBP in Raman

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systems offers improved performance for all the back-propagated bandwidths studied with a maximum improvement for FF-DBP. The Raman amplified system using only EDC outperforms the EDFA system even with the use of DBP with a small number of back-propagated channels. For the analysed scenario, DBP needs to be carried out over approximately 70 channels in the EDFA system, which corresponds roughly to 45% of the transmitted bandwidth, to obtain the same performance than the distributed Raman system using only EDC.

The system throughput is directly related to the SNR and the modulation format used to transmit information. Therefore, different gains in SNR after performing DBP will be translated into different system throughputs. Mutual information (MI) represents the maximum achievable rate at which a communication system can reliably transmit information, and has been proposed to characterise optical communication systems [15, 17]. In order to quantify the effects of the use of DBP for both studied amplification schemes on the achievable rates, MI for 64- and 256QAM was estimated. The obtained SNRs values from Fig. 4(a) were used to calculate MI using Monte-Carlo estimation and assuming an additive white Gaussian noise (AWGN) channel, as described in [15] Eq. (3), and is shown as a function of the number of back-propagated channels in Fig. 4(c). For example, if 64-QAM is used as the modulation format, the 16.2 dB SNR obtained for the EDFA with EDC system are translated into 10 bits per symbol. As expected, the highest achievable rates are given by the modulation format with the highest number of constellation points. The highest possible MI for 64QAM, 12 bits per symbol (6 b/sym over both polarizations), is rapidly obtained when the back-propagated bandwidth is increased in the Raman system. In the EDFA system however, this value is only achieved by performing FF-DBP. The use of 256QAM offers similar gains in MI for both amplification schemes, however, the Raman system exhibits higher MI for all the studied back-propagated bandwidths due to the higher SNR offered by this amplification scheme. In general, the higher SNR and the SNR gains obtained with the use of distributed Raman amplification and DBP are translated in higher achievable rates compared to EDFA-based systems.

5. Conclusion

The performance of digital back-propagation for backward-pumped distributed Raman and EDFA-based transmission links was evaluated using the GN-model and through detailed numerical simulations. The distributed nature of backward pumped Raman amplification allows for an improved performance in both studied scenarios, with and without the use of nonlinearity compensation. The use of FF-DBP in distributed Raman amplifier-based systems offers an additional 1.3 dB gain in SNR with respect to EDFA for all evaluated distances. However, due to characteristic signal power profile of distributed Raman amplifiers, the complexity of the DBP algorithm is increased, requiring an increase of at least 25% in the number of steps per spans used. For a system utilizing the entire C-band, distributed Raman amplification was found to outperform EDFAs for any back-propagated bandwidth. In fact, only compensating for chromatic dispersion in Raman systems exhibits better performance than the use of DBP with EDFA amplification when less than 45% of the bandwidth is back-propagated. Even in the presence higher nonlinear distortions, distributed Raman amplifiers continue to be an attractive solution to increase system capacity, by showing improved performance when DBP is used leading to higher achievable information rates compared to EDFA solutions, and the possibility of extending the bandwidth beyond the conventional EDFA limitations.

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