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# Span length and information rate optimisation in optical transmission systems using single-channel digital backpropagation

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**Abstract:** The optimisation of span length when designing optical communication systems is important from both performance and cost perspectives. In this paper, the optimisation of inter-amplifier spacing and the potential increase of span length at fixed information rates in optical communication systems with practically feasible nonlinearity compensation schemes have been investigated. It is found that in DP-16QAM, DP-64QAM and DP-256QAM systems with practical transceiver noise limitations, single-channel digital backpropagation can allow a 50% reduction in the number of amplifiers without sacrificing information rates compared to systems with optimal span lengths and linear compensation.



**OCIS codes:** (060.2330) Fiber optics communications; (060.1660) Coherent communications; (060.4370) Nonlinear optics, fibers.

## References and links

1. R.-J. Essiambre, G. Kramer, P. J. Winzer, G. Foschini, and B. Goebel, "Capacity limits of optical fiber networks," J. Lightwave Technol. **28**(4), 662–701 (2010).
2. R. Dar, M. Shtaif, and M. Feder, "New bounds on the capacity of the nonlinear fiber-optic channel," Opt. Lett. **39**(2), 398–401 (2014).
3. A. Mecozzi and R.-J. Essiambre, "Nonlinear Shannon limit in pseudolinear coherent systems," J. Lightwave Technol. **30**(12), 2011–2024 (2012).
4. E. Ip and J. Kahn, "Compensation of dispersion and nonlinear impairments using digital backpropagation," J. Lightwave Technol. **26**(20), 3416–3425 (2008).
5. P. Bayvel, R. Maher, T. Xu, G. Liga, N. A. Shevchenko, D. Lavery, A. Alvarado, and R. I. Killey, "Maximizing the optical network capacity," Philos Trans A Math Phys Eng Sci **374**(2062), 20140440 (2016).
6. D. Semrau, T. Xu, N. A. Shevchenko, M. Paskov, A. Alvarado, R. I. Killey, and P. Bayvel, "Achievable information rates estimates in optically amplified transmission systems using nonlinearity compensation and probabilistic shaping," Opt. Lett. **42**(1), 121–124 (2017).
7. T. Fehenberger and N. Hanik, "Digital back-propagation of a superchannel: achievable rates and adaptation of the GN model," in *Proceedings of European Conference on Optical Communication (ECOC)*, (Institute of Electrical and Electronics Engineers, 2014), paper We.3.3.6.
8. G. Bosco, V. Curri, A. Carena, P. Poggiolini, and F. Forghieri, "On the performance of Nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers," J. Lightwave Technol. **29**(1), 53–61 (2011).
9. J. Cho, X. Chen, S. Chandrasekhar, G. Raybon, R. Dar, L. Schmalen, E. Burrows, A. Ademiecki, S. Corteselli, Y. Pan, D. Correa, B. McKay, S. Zsigmond, P. Winzer, and S. Grubb, "Trans-Atlantic field trial using probabilistically shaped 64-QAM at high spectral efficiencies and single-carrier real-time 250-Gb/s 16-QAM," in *Proceedings of Optical Fiber Communications Conference*, (Optical Society of America, 2017), paper Th5B.3.
10. J. Yu, Z. Dong, H.-C. Chien, Z. Jia, X. Li, D. Huo, M. Gunkel, P. Wagner, H. Mayer, and A. Schippel, "Transmission of 200 G PDM-CSRZ-QPSK and PDM-16 QAM With a SE of 4 b/s/Hz," J. Lightwave Technol. **31**(4), 515–522 (2013).
11. N. J. Doran and A. D. Ellis, "Minimising total energy requirements in amplified links by optimising amplifier spacing," Opt. Express **22**(16), 19810–19817 (2014).

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12. N. J. Doran and A. D. Ellis, "Optical link design for minimum power consumption and maximum capacity," in *Proceedings of European Conference on Optical Communication (ECOC)*, (Institute of Electrical and Electronics Engineers, 2014), paper P4.9.
13. J. D. Ania-Castañón, I. O. Nasieva, S. K. Turitsyn, N. Brochier, and E. Pincemin, "Optimal span length in high-speed transmission systems with hybrid Raman-erbium-doped fiber amplification," Opt. Lett. **30**(1), 23–25 (2005).
14. W. A. Wood, S. Ten, I. Roudas, P. Sterlingov, N. Kaliteevskiy, J. Downie, and M. Rukosueva, "Relative importance of optical fiber effective area and attenuation in span length optimization of ultra-long 100 Gbps PM-QPSK systems," in *Proceedings of SubOptic conference* (2013), paper TU1C–3.
15. T. Fehenberger, A. Alvarado, P. Bayvel, and N. Hanik, "On achievable rates for long-haul fiber-optic communications," Opt. Express **23**(7), 9183–9191 (2015).
16. P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, and F. Forghieri, "A simple and effective closed-form GN model correction formula accounting for signal non-Gaussian distribution," J. Lightwave Technol. **33**(2), 459–473 (2015).
17. R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, "Accumulation of nonlinear interference noise in fiber-optic systems," Opt. Express **22**(12), 14199–14211 (2014).
18. L. Beygi, N. V. Irukulapati, E. Agrell, P. Johannisson, M. Karlsson, H. Wymeersch, P. Serena, and A. Bononi, "On nonlinearly-induced noise in single-channel optical links with digital backpropagation," Opt. Express **21**(22), 26376–26386 (2013).
19. T. Xu, N. A. Shevchenko, D. Lavery, D. Semrau, G. Liga, A. Alvarado, R. I. Killey, and P. Bayvel, "Modulation format dependence of digital nonlinearity compensation performance in optical fibre communication systems," Opt. Express **25**(4), 3311–3326 (2017).
20. G. Bosco, A. Carena, V. Curri, R. Gaudino, P. Poggiolini, and S. Benedetto, "Suppression of spurious tones induced by the split-step method in fiber systems simulations," IEEE Photonics Technol. Lett. **12**(5), 489–491 (2000).
21. G. P. Agrawal, *Fiber-optic Communication systems, 4th ed.* (John Wiley & Sons, Inc., 2010).
22. J. Delavaux and J. Nagel, "Multi-stage erbium-doped fiber amplifier designs," J. Lightwave Technol. **13**(5), 703–720 (1995).
23. H. Masuda and A. Takada, "High gain two-stage amplification with erbium-doped fibre amplifier," Electron. Lett. **26**(10), 661–662 (1990).
24. T. Xu, G. Jacobsen, S. Popov, J. Li, E. Vanin, K. Wang, A. T. Friberg, and Y. Zhang, "Chromatic dispersion compensation in coherent transmission system using digital filters," Opt. Express **18**(15), 16243–16257 (2010).
25. R. Asif, C. Lin, and B. Schmauss, "Impact of channel baud-rate on logarithmic digital backward propagation in DP-QPSK system with uncompensated transmission links," Opt. Commun. **284**(24), 5673–5677 (2011).
26. L. Zhu and G. Li, "Folded digital backward propagation for dispersion-managed fiber-optic transmission," Opt. Express **19**(7), 5953–5959 (2011).
27. A. Napoli, Z. Maalej, V. Sleiffer, M. Kuschnerov, D. Rafique, E. Timmers, B. Spinnler, T. Rahman, L. Coelho, and N. Hanik, "Reduced complexity digital back-propagation methods for optical communication systems," J. Lightwave Technol. **32**(7), 1351–1362 (2014).
28. L. Du, D. Rafique, A. Napoli, B. Spinnler, A. D. Ellis, M. Kuschnerov, and A. Lowery, "Digital fiber nonlinearity compensation," IEEE Signal Process. Mag. **31**(2), 46–56 (2014).
29. D. Rafique, "Fiber nonlinearity compensation: commercial applications and complexity analysis," J. Lightwave Technol. **34**(2), 544–553 (2016).
30. L. Galdino, D. Semrau, D. Lavery, G. Saavedra, C. B. Czegledi, E. Agrell, R. I. Killey, and P. Bayvel, "On the limits of digital back-propagation in the presence of transceiver noise," Opt. Express **25**(4), 4564–4578 (2017).
31. L. Szczecinski and A. Alvarado, *Bit-Interleaved Coded Modulation: Fundamentals, Analysis and Design*. (John Wiley& Sons, Inc., 2015).
32. G. Liga, A. Alvarado, E. Agrell, and P. Bayvel, "Information rates of next-generation long-haul optical fiber systems using coded modulation," J. Lightwave Technol. **35**(1), 113–123 (2017).
33. R. Dar and P. J. Winzer, "On the limits of digital back-propagation in fully loaded WDM systems," IEEE Photonics Technol. Lett. **28**(11), 1253–1256 (2016).
34. M. Secondini, E. Forestieri, and G. Prati, "Achievable information rate in nonlinear WDM fiber-optic systems with arbitrary modulation formats and dispersion maps," J. Lightwave Technol. **31**(23), 3839–3852 (2013).
35. A. Yariv, "Signal-to-noise considerations in fiber links with periodic or distributed optical amplification," Opt. Lett. **15**(19), 1064–1066 (1990).


## 1. Introduction

The increasing information rate demands on optical fibre links require Nyquist-spaced wavelength division multiplexing (WDM) and high order dual-polarisation quadrature amplitude modulation formats (DP-QAM) [1]. Advanced digital signal processing (DSP) is an integral part of these spectrally efficient systems, since the densely spaced channels experience strong nonlinear interactions which limit the maximum amount of information that can be transmitted with an arbitrarily small post-correction error [2–7].

Studies of optical communication systems performance often assume a span length which does not necessarily minimise the transmission distortions [1,8–10]. Although for some systems the amplifier spacing is predetermined, in new submarine systems the span length is more flexible to adjustments. Due to the trade-off between the amplified spontaneous emission (ASE) noise from optical amplifiers and the nonlinear distortions in fibres there is a non-trivial optimal span length. For instance, it has been studied in terms of energy optimisation [11,12], nonlinear phase shift in hybrid Raman-EDFA-amplified on-off keying systems [13], and Q-factor in quadrature phase-shift keying (QPSK) ultra-long haul submarine systems [14]. However, the effects of modulation format and nonlinear compensation have not been reported. Further, no investigation of the information rates, which is an important figure of merit in coded communication systems, has been performed.

In this paper, we examine the mutual information (MI) as an indication of information rates [15] when the span length is varied in practical WDM systems with erbium doped fibre amplifiers (EDFAs) and transmitter and receiver limited in SNR performance. The MI is compared for DSP schemes with electronic dispersion compensation (EDC) and single-channel digital backpropagation (1ch-DBP) with DP-QPSK, DP-16QAM and DP-64QAM. For comparison reasons the achievable information rate results for DP-256QAM are also examined, although the significant reduction of MI and the complexity of generation of this very high order modulation format may dictate its limited applicability at such long transmission distances. Since the closed-form nonlinear interference analytical model [16–19] is not valid for spans of standard single mode fibre (SSMF) which are shorter than 50 km, we obtain our results through numerical simulations to cover span lengths from 20 km to 120 km. For the first time to our knowledge, the maximum achievable MI at optimal span lengths has been studied both with and without the use of nonlinearity compensation. In particular, they show that for DP-16QAM, DP-64QAM and DP-256QAM, single-channel DBP can achieve the same MI with spans a factor of 2 longer than span-length-optimised EDC-based systems. This may lead to 50% reduction of number of amplifiers required without a decrease in information rates.

## 2. Transmission setup

A representative system, highlighting the span length design choice issue and the role of DBP, was investigated. Table 1 summarises the system parameters used in the numerical simulations. An 11-channel 32 Gbaud Nyquist-spaced WDM system was simulated with DP-QPSK, DP-16QAM, DP-64QAM and DP-256QAM modulation formats applied. The span length was varied from 20 to 120 km. The total link distances range from 2400 to 7200 km. The SSMF is simulated based on the split-step Fourier solution of the Manakov equation with a logarithmic step-size distribution [19,20]. The EDFAs fully compensate for the loss in each fibre span and are modelled in accordance to [21]. In practice when higher gain is required a multi-stage amplification scheme, which has an impact on the noise figure of the amplifier, may need to be applied [22,23]. For the purposes of our study, concentrated on an information-theoretic aspect of short optimal span lengths, we assume a noise figure of 4.5 dB. Nevertheless, comments on the effects of the potential increase of the noise figure are provided as a discussion at the end of Section 3. The EDC is implemented using a frequency domain equaliser [24]. The DBP is realised using the reverse split-step Fourier solution of the Manakov equation with a logarithmic step-size distribution [4,19,25] with an ideal RRC filter applied to select the desired back-propagated bandwidth. The number of steps per link is kept constant for the forward and backward propagation to achieve optimal nonlinear compensation performance. However, for the single-channel DBP assumed in this work, it has been verified that using low number (e.g. 5 steps/span) of steps per span introduces a negligible penalty for all examined modulation formats and thus the presented results are valid [19].

Reduced complexity DBP algorithms have been investigated from the perspective of dispersion management [26–28]. On the other hand, because of the prohibitively increased computational cost of a full WDM bandwidth nonlinear processing, partial bandwidth DBP (PB-DBP) is considered as a promising way to ease the requirements on the chip complexity and apply DBP in commercial systems [28,29]. In our work only a single-channel (32 GHz) DBP was considered, as an illustration of a potentially low complexity way to implement DBP. The transceiver SNR of 25 dB was considered to emulate the practical transceiver noise limitations. Polarisation mode dispersion (PMD) is neglected, since it was shown that the transceiver noise greatly outweighs the impact of PMD [30]. Phase noise from the transmitter and local oscillator (LO) lasers, as well as the frequency offset between them are also neglected. In the simulation setup, the digital-to-analogue (DAC) and analogue-to-digital (ADC) converters, current driver and I/Q modulator are assumed ideal. Figure 1 illustrates the simulation setup of the multi-channel Nyquist-spaced superchannel optical transmission system.

**Table 1. Transmission system parameters**

| Parameter | Value |
|---|---|
| Symbol rate | 32 Gbaud |
| Channel spacing | 32 GHz |
| Central wavelength | 1550 nm |
| Number of channels | 11 |
| RRC filter roll-off | 0.1% |
| Transceiver SNR | 25 dB |
| Fibre attenuation | 0.2 dB/km |
| Chromatic dispersion | 17 ps/nm/km |
| Nonlinear coefficient | 1.2 /W/km |
| EDFA noise figure | 4.5 dB |

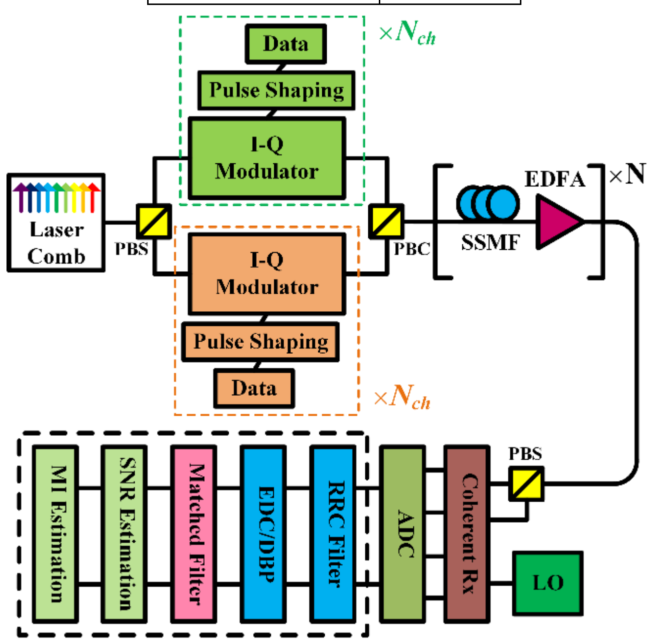


Fig. 1. Schematics of the Nyquist-spaced optical fibre communication system using EDC and single-channel DBP. PBS: polarisation beam splitter, PBC: polarisation beam combiner, LO: local oscillator, ADC: analogue-to-digital converter, MI: mutual information, $N_{ch}$: number of WDM channels, N: number of spans.

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For any combination of modulation format, compensation scheme and total distance the input power is varied for the different span length scenarios and the SNR is estimated to find an optimum launch power. Operating at the respective optimum powers for EDC and single-channel DBP we numerically obtain the soft-decision MI for the central channel via the Gauss-Hermite quadratures [31], based on the SNR and a Gaussian noise assumption on the channel [31,32] (which applies to operation at the optimum launch power regimes in both EDC and DBP cases in dispersion-unmanaged optical communication systems [15,16,33]).

For the discrete-time memoryless additive white Gaussian noise (AWGN) channel the input-output relationship is given by:

$$Y = X + Z \tag{1}$$

where $X$ and $Y$ respectively denote the complex-valued input and output symbols in each state of polarisation. $Z$ is an independent complex-valued zero-mean circularly symmetric Gaussian random variable with variance:

$$\sigma_z^2 = \mathrm{Var}\left[\left|Z\right|\right] = \mathrm{E}\left[\left|Y - X\right|^2\right] \tag{2}$$

where *E[.]* denotes expectation. The average transmitted power is $\sigma_x^2 = \mathrm{E}\left[\left|X\right|^2\right]$ and thus the SNR for the AWGN channel can be written as:

$$\mathrm{SNR} = \frac{\sigma_x^2}{\sigma_z^2}. \tag{3}$$

The symbol-wise soft decision MI for a discrete DP-QAM input distribution is then defined as:

$$\mathrm{MI} = \frac{2}{M} \sum_{x \in \mathbf{X}} \int_{\mathbf{C}} P_{Y|X}\left(y \mid x\right) \log_2 \frac{p_{Y|X}\left(y \mid x\right)}{\frac{1}{M} \sum_{x' \in \mathbf{X}} p_{Y|X}\left(y \mid x'\right)} dy, \tag{4}$$

where $X = \{X_1, \ldots, X_M\}$ is the set of possible transmitted symbols, **C** is the set of complex numbers. $M$ is the cardinality of the input signal constellation. With respect to the AWGN assumption on the channel the conditional probability density function $p_{Y|X}(y|x)$, also known as the channel law, is given by [15,31,34]):

$$p_{Y|X}\left(y \mid x\right) = \frac{1}{\pi \sigma_z^2} \exp\left(-\frac{\left|y - x\right|^2}{\sigma_z^2}\right). \tag{5}$$

Equations (1) to Eq. (5) are used to generate Fig. 2, which gives the relationship between MI and SNR for DP-QPSK, DP-16QAM, DP-64QAM and DP-256QAM under the AWGN channel model assumption. This applies to the optimum launch power regimes (in both EDC and DBP cases) in dispersion-unmanaged optical communication systems [15,16,19,33].

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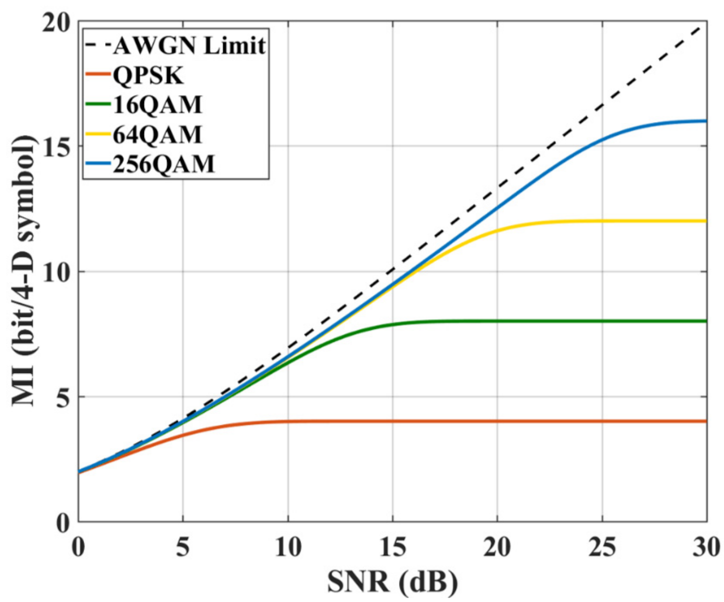


Fig. 2. MI as a function of SNR for DP-QPSK, DP-16QAM, DP-64QAM and DP-256QAM based on the assumption of an AWGN channel model.

## 3. Results and discussions

In Table 2 we summarise the obtained optimum launch powers at different span lengths for DP-16QAM modulation format at 2400, 4800 and 7200 km total distance for the cases of linear (EDC) and nonlinear (single-channel DBP) compensation.

**Table 2. DP-16QAM optimum launch powers for different span lengths at total distances of 2400, 4800 and 7200 km with both EDC and single-channel DBP**

| | Optimum launch power EDC (dBm) at total distance: | | | Optimum launch power 1ch-DBP (dBm) at total distance: | | |
|---|---|---|---|---|---|---|
| Span length (km) | 2400 km | 4800 km | 7200 km | 2400 km | 4800 km | 7200 km |
| 20 | −6 | −6.5 | −6.5 | −4.5 | −4.5 | −5 |
| 30 | −5.5 | −5.5 | −5.5 | −4 | −4 | −4.5 |
| 40 | −4.5 | −5 | −5 | −3.5 | −3.5 | −3.5 |
| 50 | −4 | −4.5 | −4.5 | −3 | −3 | −3.5 |
| 60 | −3 | −3 | −3.5 | −2.5 | −2.5 | −2.5 |
| 80 | −2 | −2 | −2.5 | −1.5 | −1.5 | −1.5 |
| 100 | −0.5 | −0.5 | −1 | 0 | 0 | 0 |
| 120 | 1 | 0.5 | 0.5 | 1.5 | 1 | 1 |

The optimum launch powers are higher in the single-channel DBP case compared to EDC only. As the span length increases in both cases the launch powers also increase. For longer total distances there is a slight reduction in optimum launch powers because of the coherent accumulation of nonlinearity. The optimum launch powers were confirmed to be the same for DP-16QAM, DP-64QAM and DP-256QAM, while the values for DP-QPSK are slightly higher (in the range of 0.5 dB). This is due to the advantageous nonlinearity performance of the QPSK format which has been confirmed in previous studies [19]. The optimum powers were used for investigation of the MI as a function of span length in the subsequent figures in this section. The MI performance of the DP-QPSK modulation format is saturated at its maximum possible 4 bit/symbol for all examined span lengths at any total system reach

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considered. Therefore most of the discussions and comparisons in this section are concentrated on the DP-QAM formats.

Figure 3 shows the obtained MI (two polarisations) for different modulation formats as a function of span length at 2400 km total system reach for both EDC and single-channel DBP. At this distance, the MI for DP-QPSK reaches its maximum possible value (4 bit/symbol) for any span length in both compensation schemes and 120 km per span can be utilised without sacrificing information rates. This modulation format allows utilisation of spans longer than the commonly assumed 80 km/span at ultra-long haul distances. The results further show that the longest span length that achieves 8 bit/symbol for DP-16QAM is 60 km. For higher order modulation formats, in both the EDC and single-channel DBP schemes, the MI is maximal at the span length of 30 km. The optimal span length is a trade-off between the ASE noise originating from the optical amplifiers and the nonlinear interactions in the transmission fibre. The combined contribution of these terms is minimised at 30 km span lengths for the EDFA-amplified system under investigation. For longer or shorter spans the MI performance decreases. In particular, the MI for DP-64QAM at optimum span length with EDC is 10.3 bit/symbol, while for the DBP case it is 10.8 bit/symbol. The maximum MI in DP-256QAM systems is 10.6 bit/symbol for EDC and 11.1 bit/symbol for single-channel DBP. Compared to the 80 km/span scenario, utilisation of optimum span lengths for DP-64QAM and EDC gives 1.3 bit/symbol gain in MI. In the case of single-channel DBP the increase is 1.4 bit/symbol. For DP-256QAM these enhancements are 1.4 and 1.6 bit/symbol for EDC and single-channel DBP, respectively. It is also worth noting that if the noise figure of the EDFAs is increased, the differences in MI between shorter (below 60 km) and longer spans further grow. This is due to the increased ASE noise whose effects are greater for long spans. Therefore, an increase in the noise figure of the amplifiers will not alter the conclusions in our study which concentrates on the optimal span lengths.

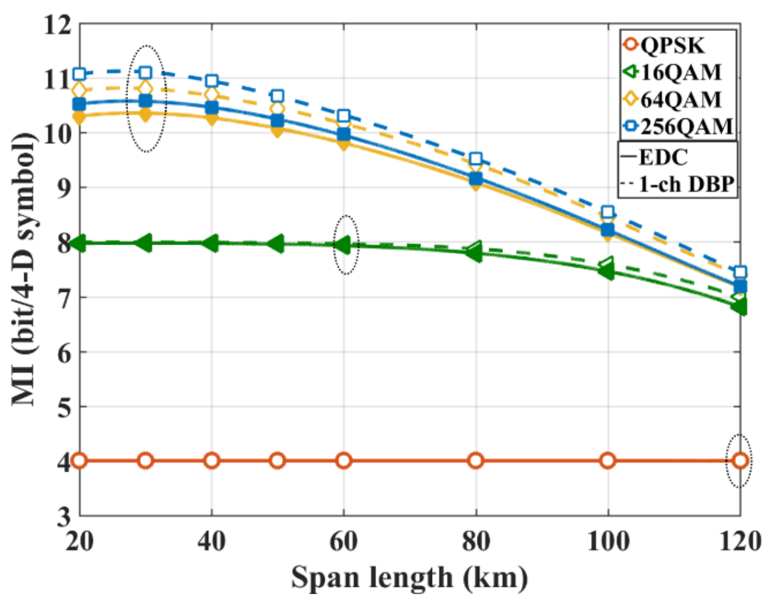


Fig. 3. MI versus span length for different modulation formats at 2400 km total reach in EDC and single-channel DBP schemes. Span lengths that achieve maximum MI are encircled with black dashed line.

Figure 4 shows the dependence of MI on span length for the DP-64QAM format for different transmission distances. At all distances, the optimum span length for both EDC and single-channel DBP cases is 30 km. At 4800 km, a total system reach for a maximum MI for EDC is 8.8 bit/symbol, while single-channel DBP improves this to 9.4 bit/symbol. The MI at optimal span length at 7200 km is 7.8 bit/symbol for EDC and is increased to 8.5 bit/symbol with single-channel DBP. Furthermore, at all distances the enhancement of MI due to single-channel DBP is more significant when shorter spans are considered and reduces for longer span lengths, as expected. For example, at 7200 km it decays from 0.7 bit/symbol at 20 km/span to 0.3 bit/symbol at 120 km/span. The increase of MI is stronger for shorter spans when single-channel DBP is applied because as the span length increases, the signal-signal interactions become less significant compared to noise from the amplifiers and the interactions between signal and noise. For this reason the MI performance at optimum span lengths compared to 80 km/span is further enhanced as the total system reach increases from 2400 km to 7200 km. For the single-channel DBP case the difference in MI between 30 and 80 km/span is 1.4 bit/symbol at 2400 km and these gains grow to 1.6 and 1.7 bit/symbol at total distances 4800 and 7200 km, respectively. For the EDC this MI enhancement is 1.3, 1.4 and 1.5 bit/symbol at respectively 2400, 4800 and 7200 km total distance.

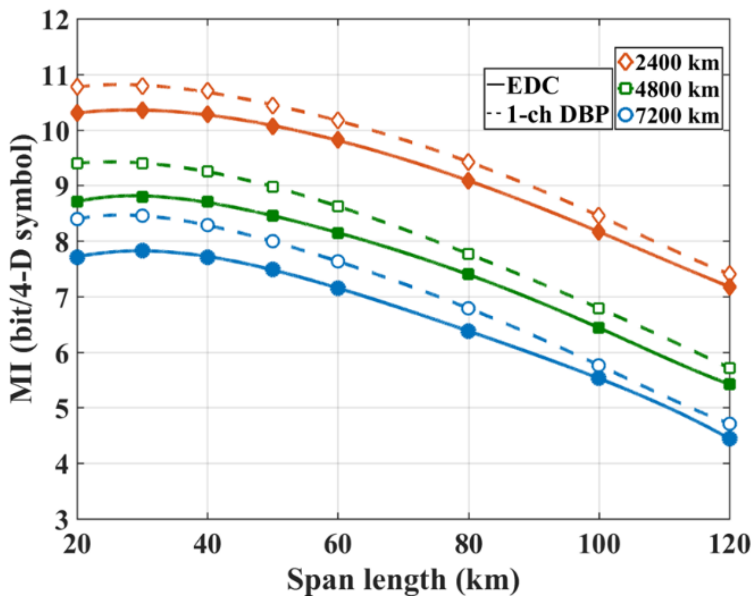


Fig. 4. MI versus span length for DP-64QAM at varied total transmission distance with EDC and single-channel DBP.

Single-channel DBP can be applied to increase the inter-amplifier spacing and at the same time achieve the information rates of the span-length-optimised EDC systems. Therefore, at the maximum possible information rates, the number of amplifiers and, as a consequence, the cost of the system will be reduced substantially.

Figure 5 illustrates the possible increase in span length at a target MI level when single-channel DBP is applied for DP-16QAM, DP-64QAM and DP-256QAM and total distances of 2400, 4800 and 7200 km, respectively. The highest MI of the EDC schemes for all modulation formats and at any total system reach was achieved at approximately twice the span length with single-channel DBP. For instance, the maximum possible MI for DP-256QAM format with EDC at 4800 km is 8.8 bit/symbol and it requires a system that employs 30 km spans. With single-channel DBP, an MI of 8.8 bit/symbol can be achieved at the same total distance using twice the span length, 60 km. Consequently, information rates, identical to those optimal for EDC schemes, can be achieved, while a 50% decrease in the number of amplifiers can be realised. As the total system reach increases, the reduction of the required number of amplifiers might provide significant cost savings through single-channel DBP.

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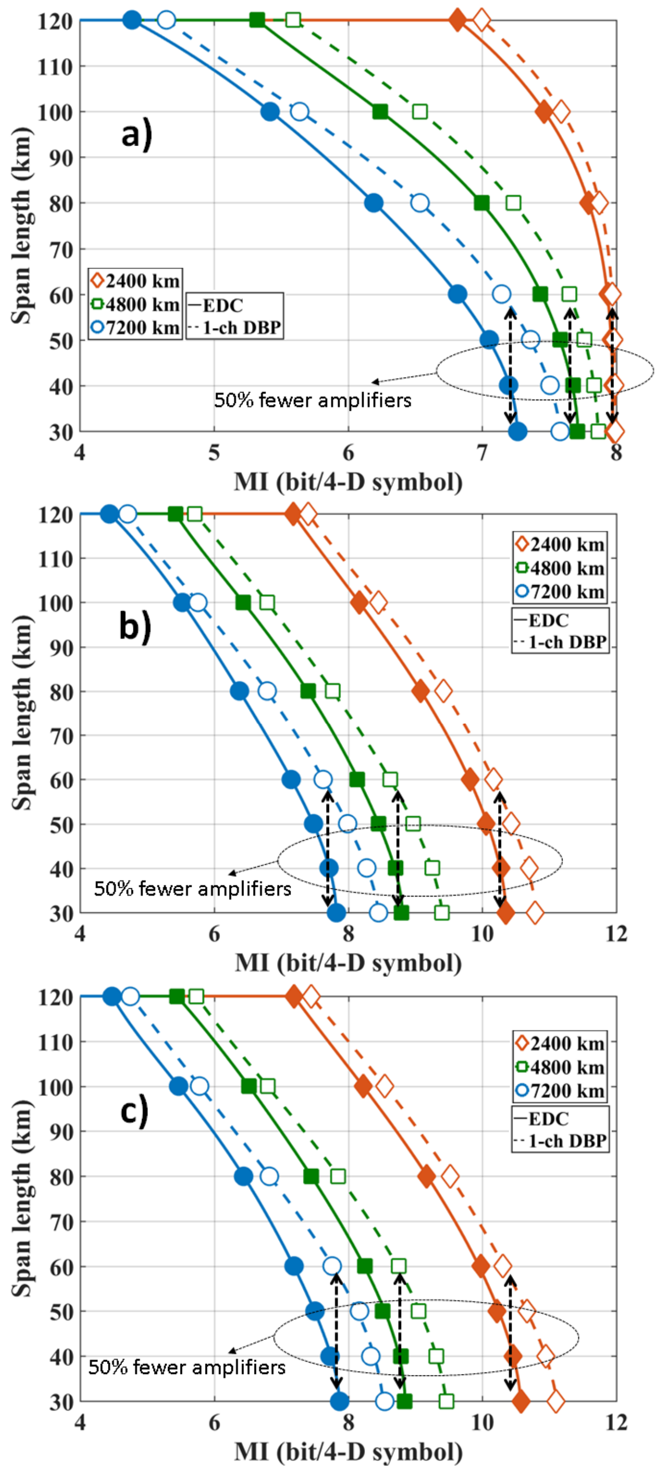


Fig. 5. Span length as a function of target mutual information at different total system reach for DP-16QAM (a), DP-64QAM (b), and DP-256QAM (c) with single-channel DBP and EDC. The maximum MI values in linear compensation schemes and the span length at which single-channel DBP achieves them are indicated.

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A span length increase from 30 to 60 km changes the gains of the optical amplifiers assumed to fully compensate the span loss. Although the 60 km spans require twice the EDFA gain (in logarithmic units) versus the 30 km spans, this does not require twice the complexity. To a reasonable approximation, the high gain EDFA requires only an increase in pump power to compensate for the additional attenuation in the longer span. Therefore a significant cost increase from the EDFA perspective might be avoided.

Although it is achieved through a relatively low-complexity way of applying nonlinear compensation such as single-channel DBP, the reduction in the number of optical amplifiers without a corresponding decrease in information rates when compared to systems with optimised span lengths and linear compensation still requires added complexity of the integrated electronic components in the transceivers. Therefore, such an approach, which provides more freedom in optical link design, benefits from the rapid progress in circuit integration and the undergoing research efforts in DBP complexity reduction.

Another interesting aspect of such an investigation, which will be studied in future work, is the case of Raman-amplified systems. For such systems, it has been proven that the optimal optical signal-to-noise ratio (OSNR) performance is achieved by asymptotically vanishing span length, equivalent to ideal distributed amplification [35]. In a practical study of hybrid Raman-EDFA amplification in dispersion-managed links it was found that optimal span length in terms of minimisation of the nonlinear phase shift is determined by the pump configuration as well as the particular dispersion map that is considered [13].

## 4. Conclusions

The span length design choice issue raised by single-channel DBP, which is a feasible digital nonlinearity compensation technique, was studied in terms of information rates for different modulation formats considering practical transceiver limitations. Reductions in the number of amplifiers, at fixed information rates, were investigated from the perspective of applying single-channel digital backpropagation instead of compensating only linear channel impairments. The MI variation with span length at different total system reach was examined for DP-QPSK, DP-16QAM, DP-64QAM, and DP-256QAM formats with linear and nonlinear compensation. Practical schemes that assume transceiver noise limitations were considered to obtain realistic nonlinear compensation gains. It was found that at shorter spans these gains are more significant and decrease with span length. It was shown that inter-amplifier spacing can be doubled at the same information rates as in span-length-optimised systems with linear compensation. Consequently, implementing single-channel DBP can effectively reduce the total number of amplifiers in the system by 50% without sacrificing information rates. Such an approach can lead to significant cost savings in commercial submarine and terrestrial optical transmission systems.

Future research directions of the study are the extension to a greater number of transmitted WDM channels and a greater digitally backpropagated bandwidth. Different amplification schemes including Raman and hybrid amplification will also be examined.

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