On the bandwidth dependent performance of split transmitter-receiver optical fiber nonlinearity compensation

DOMANIÇ LAVERY,[1,*] ROBERT MAHER,[1] GABRIELE LIGA,[1] DANIEL SEMRAU,[1] LIDIA GALDINO,[1] AND POLINA BAYVEL[1]

[1] *Optical Networks Group, Department of Electronic & Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom*
[*] *d.lavery@ee.ucl.ac.uk*

Abstract: The Gaussian noise model is used to estimate the performance of three digital nonlinearity compensation (NLC) algorithms in C-band, long-haul, optical fiber transmission, when the span length and NLC bandwidth are independently varied. The algorithms are receiver-side digital backpropagation (DBP), transmitter-side DBP (digital precompensation), and Split NLC (an equal division of DBP between transmitter and receiver). For transmission over 100×100 km spans, the model predicts a 0.2 dB increase in SNR when applying Split NLC (versus DBP) to a single 32 GBd channel (from 0.4 dB to 0.6 dB), monotonically increasing with NLC bandwidth up to to 1.6 dB for full-field NLC. The underlying assumptions of this model and the practical considerations for implementation of Split NLC are discussed. This work demonstrates, theoretically, that, regardless of the transmission scenario, it is always beneficial to divide NLC between transmitter and receiver, and identifies the transmission regimes where Split NLC is particularly advantageous.

OCIS codes: (060.4510) Optical Communications; (060.1660) Coherent Communications.

References and links

1. R. Maher, A. Alvarado, D. Lavery, and P. Bayvel, "Increasing the information rates of optical communications via coded modulation: a study of transceiver performance," Scientific Reports **6**, 21278 (2016).
2. E. Temprana, E. Myslivets, L. Liu, V. Ataie, A. Wiberg, B. Kuo, N. Alic, and S. Radic, "Two-fold transmission reach enhancement enabled by transmitter-side digital backpropagation and optical frequency comb-derived information carriers," Opt. Express **23**, 20774–20783 (2015).
3. D. Lavery, D. Ives, G. Liga, A. Alvarado, S. Savory, and P. Bayvel, "The benefit of split nonlinearity compensation for single channel optical fiber communications," Photon. Technol. Let. **28**(17), 1803–1806 (2016).
4. R. Dar and P. J. Winzer,"On the limits of digital back-propagation in fully loaded WDM systems," Photon. Technol. Let. **28**(11), 1253—1256 (2016).
5. A. D. Ellis, M. E. McCarthy, M. A. Z. Al-Khateeb, and S. Sygletos, "Capacity limits of systems employing multiple optical phase conjugators," Opt. Express **23**(16), 20381–20393 (2015)
6. E. Ip, "Nonlinear Compensation Using Backpropagation for Polarization-Multiplexed Transmission," J. Lightwave Technol. **28**(6), 939–951 (2010).
7. G. Liga, T. Xu, A. Alvarado, R. I. Killey, and P. Bayvel, "On the performance of multichannel digital backpropagation in high-capacity long-haul optical transmission," Opt. Express **22**(24), 30053–30062 (2014).
8. F. Yaman and G. Li, "Nonlinear impairment compensation for polarization-division multiplexed WDM transmission using digital backward propagation," IEEE Photonics Journal **2**(5), 816–832, (2010).
9. P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, and F. Forghieri, "The GN-model of fiber non-linear propagation and its applications," J. Lightw. Technol. **32**(4), 694–721 (2014).
10. A. Carena, G. Bosco, V. Curri, Y. Jiang, P. Poggiolini and F. Forghieri, "EGN model of non-linear fiber propagation," Opt. Express **22**(13), 16335–16362 (2014).
11. 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. Lightw. Technol. **33**(2), 459–473 (2015).
12. R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, "Properties of nonlinear noise in long, dispersion-uncompensated fiber links," Opt. Express **21**(22), 25685–25699 (2013)
13. M. Secondini and E. Forestieri, "Analytical Fiber-Optic Channel Model in the Presence of Cross-Phase Modulation," Photon. Technol. Let. **24**(22), 2016–2019 (2012).

14. A. D. Ellis, S. T. Le, M. A. Z. Al-Khateeb, S. K. Turitsyn, G. Liga, D. Lavery, T. Xu, and P. Bayvel, “The impact of phase conjugation on the nonlinear-shannon limit: The difference between optical and electrical phase conjugation,” in “IEEE Summer Topicals Meeting Series,” 209–210 (2015).
15. T. Tanimura, M. Nölle, J. K. Fischer, and C. Schubert, “Analytical results on back propagation nonlinear compensation with coherent detection,” Opt. Express **20**(27), 28779–28785 (2012).
16. J. C. Cartledge, F. P. Guiomar, F. R. Kschischang, G. Liga and M. P. Yankov, “Digital signal processing for fiber nonlinearities,” To appear in Opt. Express nonlinearity mitigation special issue (2017).
17. E. Ip and J. M. Kahn, “Compensation of dispersion and nonlinear impairments using digital backpropagation,” J. Lightwave Technol. **26**(20), 3416–3425 (2008).
18. S. J. Savory, “Optimum electronic dispersion compensation strategies for nonlinear transmission,” Elect. Let. **42**(7), 407–408 (2006).
19. T. Xu, G. Liga, D. Lavery, B. C. Thomsen, S. J. Savory, R. I. Killey, and P. Bayvel, “Equalization enhanced phase noise in Nyquist-spaced superchannel transmission systems using multi-channel digital back-propagation,” Scientific Reports **5**, 13990 (2015).
20. C. B. Czegledi, G. Liga, D Lavery, M. Karlsson, E. Agrell, S. J. Savory, and P. Bayvel, “Polarization-mode dispersion aware digital backpropagation,” in Proc. of European Conference on Optical Communication (ECOC), 1–3 (2016).
21. G. Gao, X. Chen and W. Shieh, “Influence of PMD on fiber nonlinearity compensation using digital back propagation,” Opt. Express **20**(13), 14406–14418 (2012).
22. D. S. Millar, S. Makovejis, C. Behrens, S. Hellerbrand, R. I. Killey, P. Bayvel and S. J. Savory, “Mitigation of fiber nonlinearity using a digital coherent receiver,” J. Select. Topics Quant. Electr. **16**(5), 1217–1226 (2010).
23. R. Maher, D. Lavery, D. Millar, A. Alvarado, K. Parsons, R. Killey, and P. Bayvel, “Reach enhancement of 100% for a DP-64QAM super-channel using MC-DBP,” in Proc. of Optical Fiber Communication Conference (OFC), Th4D.5 (2015).
24. R. Maher, T. Xu, L. Galdino, M. Sato, A. Alvarado, K. Shi, S. J. Savory, B. C. Thomsen, R. I. Killey, and P. Bayvel, “Spectrally shaped DP-16QAM super-channel transmission with multi-channel digital back-propagation,” Scientific Reports **5**, 8214 (2015).
25. E. Ip, Y. K. Huang, Y. Shao, B. Zhu, D. Peckham, R. Lingle, “3 $\times$ 112-Gb/s DP-16QAM Transmission over 3580 km of ULAF with interchannel nonlinearity compensation,” in IEEE Photonic Society WEE3 (2011).
26. N. K. Fontaine, X. Liu, S. Chandrasekhar, R. Ryf, S. Randel, P. Winzer, R. Delbue, P. Pupalaikis, A. Sureka “Fiber nonlinearity compensation by digital backpropagation of an entire 1.2-Tb/s superchannel using a full-field spectrally-sliced receiver,” in Proc. of European Conference on Optical Communication (ECOC), Mo.3.D.5 (2013).
27. C. Lin, S. Chandrasekhar and P. J. Winzer, “Experimental study of the limits of digital nonlinearity compensation in DWDM systems,” in Proc. of Optical Fiber Communication Conference (OFC), Th4D.4, (2015).
28. E. Temprana, E. Myslivets, B. P.-P. Kuo, N. Alic, and S. Radic “Transmitter-Side Digital Back Propagation With Optical Injection-Locked Frequency Referenced Carriers,” J. Lightwave Technol. **34**(15), 3544–3549 (2016).
29. E. Temprana, E. Myslivets, V. Ataie, B. P.-P. Kuo, N. Alic, V. Vusirikala, V. Dangui and S. Radic “Demonstration of coherent transmission reach tripling by frequency-referenced nonlinearity pre-compensation in EDFA-only SMF Link,” In Proc. of European Conference on Optical Communication (ECOC), 376–378 (2016).
30. A. J. Lowery “Fiber nonlinearity pre- and post-compensation for long-haul optical links using OFDM,” Opt. Express **15**(20), 12965–12970 (2007).
31. W. Shieh and K. P. Ho, “Equalization-enhanced phase noise for coherent detection systems using electronic digital signal processing,” Opt. Express **16**(20), 15718–15727 (2008).
32. I. Fatadin and S. J. Savory, “Impact of phase to amplitude noise conversion in coherent optical systems with digital dispersion compensation,” Opt. Express **18**(15), 16273–16278 (2010).
33. G. Liga, C. B. Czegledi, E. Agrell, R. I. Killey, and P. Bayvel, “Ultra-wideband nonlinearity compensation performance in the presence of PMD”, In Proc. of European Conference on Optical Communication (ECOC), paper P1.SC3.9 (2016).
34. L. Galdino, G. Liga, G. Saavedra, D. Ives, R. Maher, A. Alvarado, S. Savory, R. Killey and P. Bayvel, “Experimental demonstration of modulation-dependent nonlinear interference in optical fibre communication,” In Proc. of European Conference on Optical Communication (ECOC), Th.2.C.5 (2016).
35. M. Secondini, G. Meloni, G. Berrettini and L. Poti, “How to use a low-cost DFB local oscillator in ultra-long-haul uncompensated coherent systems,” In Proc. of European Conference on Optical Communication (ECOC), Th.2.C.5 (2012).
36. F. Aflatouni, H. Hashemi, "Light source independent linewidth reduction of lasers", in Proc. of Optical Fiber Communication Conference (OFC), OW1G.6 (2012).
37. M. E. McCarthy, M. A. Z. Al Kahteeb, F. M. Ferreira, and A. D. Ellis, “PMD tolerant nonlinear compensation using in-line phase conjugation,” Opt. Express **24**(4), 3385–3392 (2016).
38. F. N. Hauske, M. Kuschnerov, B. Spinnler, and B. Lankl, “Optical performance monitoring in digital coherent receivers,” J. Lightwave Technol. **27**(16), 3623–3631 (2009).
39. K. Goroshko, H. Louchet, A. Richter, “Overcoming performance limitations of digital back propagation due to polarization mode dispersion,” In Proc. of International Conference on Transparent Optical Networks (ICTON), Paper Mo.B1.4 (2016).

1. Introduction

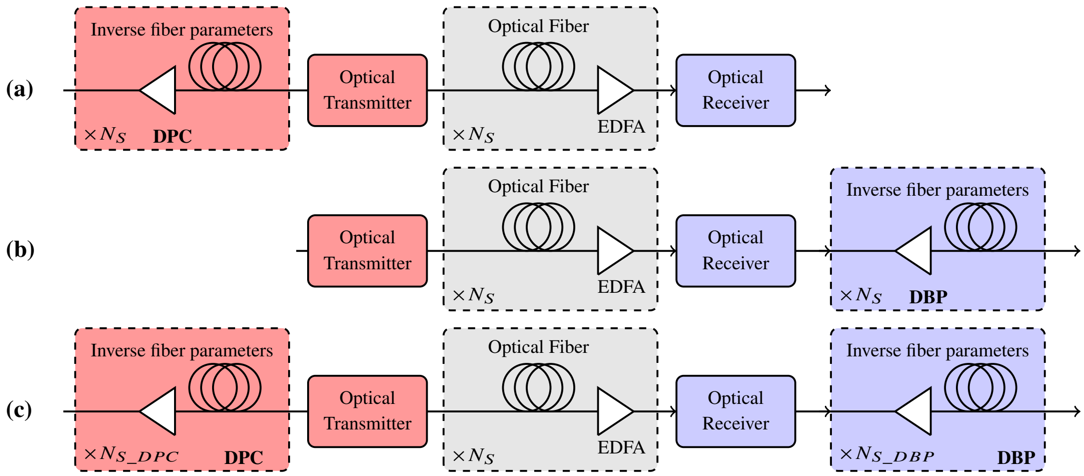

Fig. 1. Transmission models for digital nonlinearity compensation (NLC): (a) digital pre-compensation (DPC), (b) digital backpropagation (DBP) and (c) Split NLC. Note that (c) is a generalisation of (a) and (b), where it has previously been shown that the optimum configuration is $N_{S\_DPC} = N_S - N_{S\_DBP} = \lceil N_S/2 \rceil$.

In order to increase the data throughput of bandwidth-constrained, long-haul, optical fiber transmission systems, the signal-to-noise ratio (SNR), as measured at the receiver, must be improved. Since received SNR depends on all the noise contributions in a transmission link, including from within the receiver and transmitter, it is worth revisiting the commonly investigated digital signal processing (DSP) algorithms to ensure that they maximize SNR [1]. In this regard, the DSP-based optical fiber nonlinearity compensation (NLC) algorithm known as digital backpropagation (DBP) is of particular interest.

Three implementations of the DBP algorithm have been proposed, which are shown schematically in Fig. 1. The first, as shown in Fig. 1(a), is DBP applied at the transmitter, or digital precompensation (DPC). This method has the advantage of applying NLC to a notionally noise free signal [2], and theoretically improves transmission performance by up to one additional transmission span versus receiver-side DBP [3] , which is illustrated in Fig. 1(b). The most recent implementation of the DBP algorithm involves an equal division of the DSP between transmitter and receiver (hereafter 'Split NLC') [3] as shown in Fig. 1(c). Although the performance limit of these algorithms is known [4–8], the relative performance of the algorithms has not yet been analysed for practical transmission systems.

Several analytical models that estimate the nonlinear interference (NLI) coefficient and the coherence factor for digital NLC have been proposed [4, 9–13] in order to predict NLC performance. Due to the prohibitive complexity of wideband transmission system simulations, only a few numerical simulations with NLC compensation have been reported to confirm the reliability of these analytical models [3, 5, 14, 15]. Notably, however, in [16], the analytical model and numerical simulation of transmission over a 1 THz signal bandwidth using multichannel DBP are compared; this work confirms the reliability of the analytical model with NLC for wideband transmission systems.

The vast majority of analytical models [4, 5, 9–15], system simulations [6–8, 17–21] and experimental studies [22–27] of NLC are reported for receiver-side DBP performance, which is relatively straightforward to implement in laboratory conditions. The recent experimental examples have exploited advances in analog-to-digital converter (ADC) technology to achieve significantly greater performance by applying DBP to multiple channels simultaneously. Multi-channel DBP compensates for both self-channel and inter-channel interference, meaning that, in some cases, a doubling [23] of transmission reach can be experimentally realised.

Few analytical and simulation analyses of DPC performance have been reported [3], mainly due to the historically inferior performance of available digital-to-analogue converters (DAC) versus ADCs, which lead naturally to an emphasis on receiver-side NLC. Recently, the challenge of the DAC bandwidth limitation for DPC was overcome in [2], where multichannel DPC at the transmitter was experimentally demonstrated using mutually coherent sources [2, 28]; in one notable experiment achieving a trebling of transmission distance [29].

Surprisingly, little has been previously reported on the performance of Split NLC, or indeed any generalised split transmitter/receiver nonlinearity compensation [3, 5, 18, 30] and, to date, no experimental results have been presented. Advances in NLC split between transmitter and receiver have lagged behind receiver-side NLC; possibly, again, due to the availability of DACs with comparable performance to ADCs, but also due to the challenge of applying offline DSP simultaneously for signal predistortion and post-compensation. Nevertheless, it was demonstrated via numerical simulations that a simple division of the linear chromatic dispersion compensation DSP between transmitter and receiver [18] or, similarly, a simple division of a single nonlinear phase shift between transmitter and receiver [30], could give a nonlinear performance improvement.

In response to the newly available multichannel DPC technique, it was postulated and verified via numerical simulations in [3], that Split NLC could be implemented, and that applying NLC to the full signal bandwidth ('full-field' NLC), the SNR gain improvement of Split NLC over DBP would always be ≥1.5 dB. The full 1.5 dB gain is only achieved when the NLC is applied to the entire signal bandwidth simultaneously. For practical reasons, there is a question as to the performance improvement of the Split NLC algorithm when applied to just one or a few channels from the full transmitted signal bandwidth.

In this work, a closed form approximation based on the Gaussian Noise (GN)-model is used to estimate the performance of Split NLC when a varying number of channels used for NLC. Further, the system parameters which affect the performance advantage of Split NLC over DBP and DPC are theoretically analysed. Finally, considerations for practical implementations of Split NLC, in particular with regards to the influence of polarization mode dispersion (PMD), equalization enhanced phase noise (EEPN) and transceiver impairments are discussed.

2. Algorithm and performance model

The NLC algorithm in question, commonly known as digital backpropagation (DBP), is used herein as a general description of any NLC technique which digitally compensates signal-signal nonlinear interactions incurred in optical fiber transmission. NLC can be applied either over a single-wavelength channel bandwidth (leaving inter-channel nonlinear effects uncompensated) or over a bandwidth incorporating multiple channels. When no NLC is applied, the GN-model can be used to predict transmission performance. When NLC is simultaneously applied to all transmitted channels, the same GN-model can be used, but with the signal-signal interaction term removed. Finally, when only partial bandwidth NLC is applied, this can be modelled as a corresponding partial reduction in the signal-signal interaction term. We therefore model the resulting SNR in each case, assuming ideal, noiseless transceivers, as follows [3, 5, 11]:

$$SNR \approx \frac{P}{N_S P_{ASE} + \sigma_{ss}^2 + \sigma_{sn}^2}, \tag{1}$$

where the signal-signal interaction term is

$$\sigma_{ss}^2 = \left(\eta(B) N_s^{1+\epsilon_1} - \eta(B_{NLC}) N_s^{1+\epsilon_2}\right) P^3, \tag{2}$$

and the signal-noise term is

$$\sigma_{sn}^2 = 3\xi\eta(B)P^2P_{ASE}. \tag{3}$$

In Eqs. eq:intBWDBP and eq:SSinteraction, B is the total transmitted signal bandwidth, P_{ASE} is the amplified spontaneous emission (ASE) noise power (from optical amplifiers), P is the channel power, B_{NLC} is the bandwidth used for NLC, ϵ_1 and ϵ_2 are coherence parameters for self channel interference (which are close to zero for wide bandwidth transmission) evaluated using bandwidths B and B_{NLC}, respectively, N_s is the total number of spans, and η is the single span nonlinear interference factor. In Eq. eq:SNinteraction, it was assumed that the signal-noise nonlinearity factor over one span is well approximated by $3\eta(B)$ [3, 16]. The parameter ξ in Eq. eq:SNinteraction is crucial when considering Split NLC, as it depends on the number of spans and the method used for digital NLC, as detailed in [3], and is defined as follows:

$$\xi = \sum_{k=1}^{N_{S\_DPC}-1} k^{1+\epsilon_1} + \sum_{k=1}^{N_{S\_DBP}} k^{1+\epsilon_1}, \tag{4}$$

where N_{S_DPC} is the number of spans of DPC, N_{S_DBP} is the number of spans of DBP, and $N_S = N_{S\_DPC} + N_{S\_DBP}$. For Split NLC, we assume $N_{S\_DPC} = N_S - N_{S\_DBP} = \lceil N_S/2 \rceil$ [3].

What, then, are the implications of this model for the newly introduced implementations of DBP: DPC and Split NLC? Consider (1) in the limiting case of $B_{NLC} = B$. Here, the SNR gain versus DBP is simply the ratio of the ξ terms in each implementation, which is ≥1.5 dB for Split NLC (see [3]). When $B_{NLC} \ll B$, the P^3 (signal-signal) term appears to dominate the nonlinear noise expression. As this term has no implementation dependence, the performance in this regime is similar for DBP, DPC and Split NLC (except for regimes where the signal-ASE interaction term is also correspondingly large; there Split NLC retains a distinct advantage). This may be somewhat surprising, considering that the latter two implementations operate on an almost noise free signal. However, this model indicates that inter-channel nonlinear interference eliminates most of this advantage. The final case, an intermediate range when $B_{NLC} < B$ but still several times the channel bandwidth, is of particular practical interest, as the high computational complexity of digital NLC currently limits the signal bandwidth which can be simultaneously compensated. In the following section, we evaluate (1) over different bandwidths, B_{NLC}, to estimate achievable SNR gain in each scenario.

3. Results

Table 1. **Summary of system parameters**

Parameter	Value	Units
Fiber attenuation	0.2	dB/km
Dispersion parameter	17	ps/(nm · km)
Fiber nonlinear coefficient	1.2	1/(W · km)
Span length	100	km
Symbol rate	32	GBd
EDFA noise figure	5	dB
WDM channels	150	
Channel separation	32.3	GHz

The highest achievable SNR (SNR at optimum launch power) was estimated via (1) using the system parameters listed in Table 1 for transmission distances of 1000 km and 10000 km. (These are representative of metropolitan area and ultra-long-haul/submarine links, respectively.)

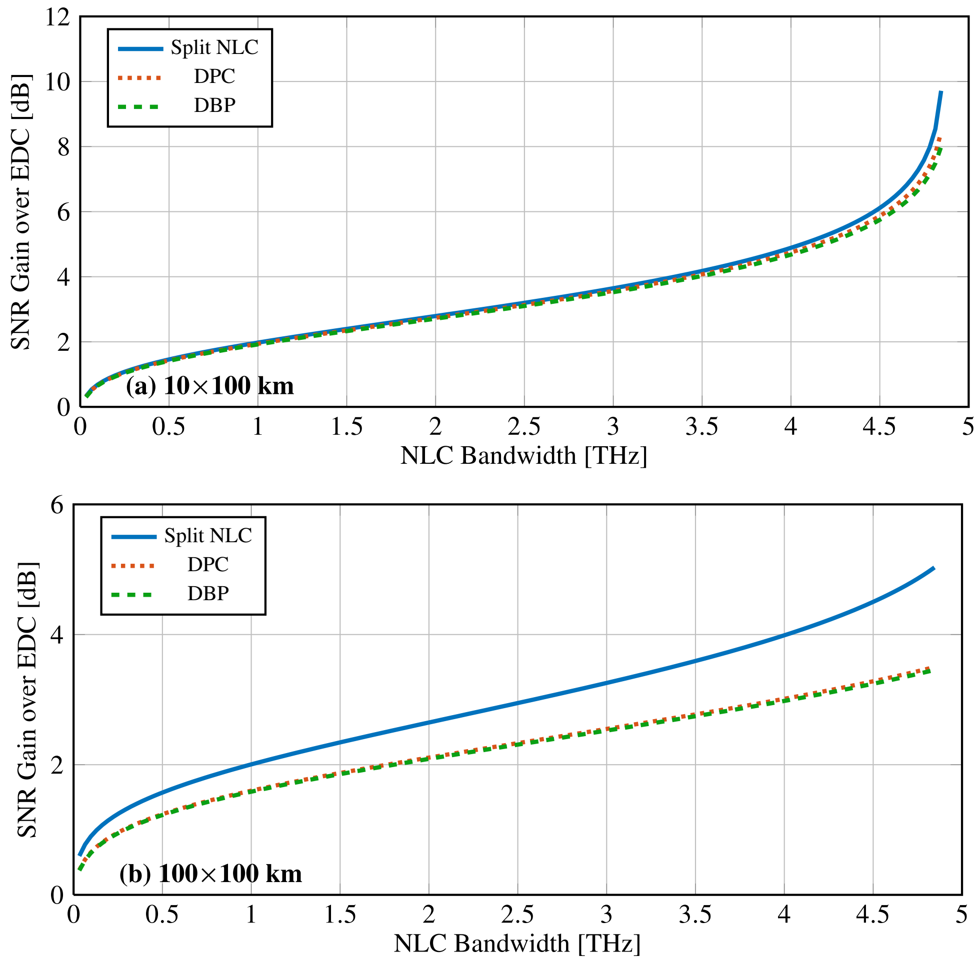

Fig. 2. Numerical evaluation of (1) to establish additional SNR gain over receiver-side DBP for both DPC and Split NLC after (a) 1000 km and (b) 10000 km transmission.

The effect of varying NLC bandwidth for the three algorithms under test is shown in Fig. 2. At both distances, Split NLC provides >1.5 dB SNR gain versus conventional (receiver-side) DBP when applied to the full transmitted signal bandwidth. The maximum SNR gain decreases with distance, and this is due to the corresponding decrease in the coherence parameter, ϵ_1, with distance. As noted in previous work [3], the asymptotic SNR gain over DBP for Split NLC is 1.5 dB ($\epsilon_1 \to 0$) for dispersion unmanaged systems. Similarly, for DPC, the largest gains are seen for wide bandwidth NLC, however the gains are smaller for DPC: 0.4 dB and 0.04 dB at 1000 km and 10000 km, respectively. This is because the gains for DPC come from the first span, only, and therefore the SNR gain over DBP will tend asymptotically to zero for long transmission distances. These results are summarised in Fig. 3(a).

The limiting case considered, above, requires a backpropagation bandwidth of almost 5 THz, and so we must ask: are SNR gains over DBP achievable for practical NLC bandwidths? Consider single channel NLC. For both transmission distances, DPC exhibits negligible gain over DBP (<0.01 dB). This is because the signal-signal (P^3) nonlinear interference term dominates the signal-ASE (P^2) term for small NLC bandwidths at short distances. As the signal-ASE term

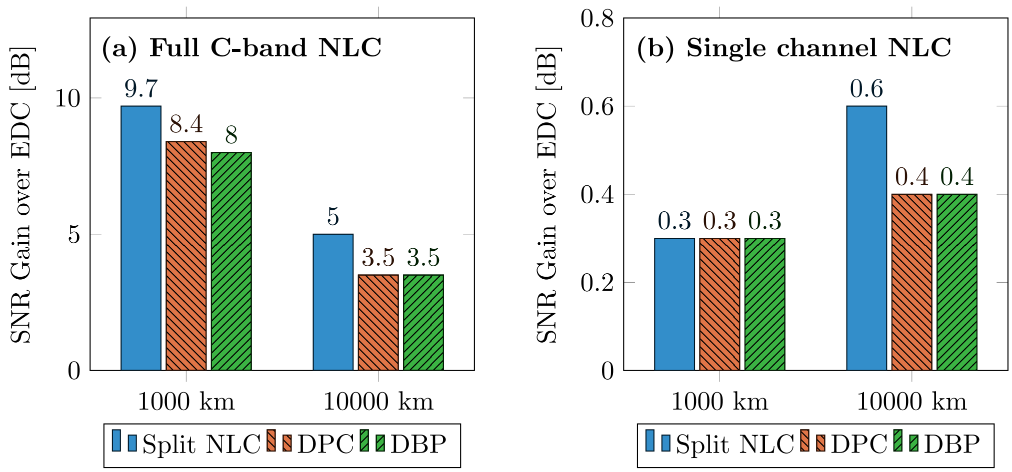

Fig. 3. The SNR improvement using different NLC algorithms, as in Fig. 2, when (a) compensating the full C-band simultaneously, and (b) compensating only a single channel from the C-band.

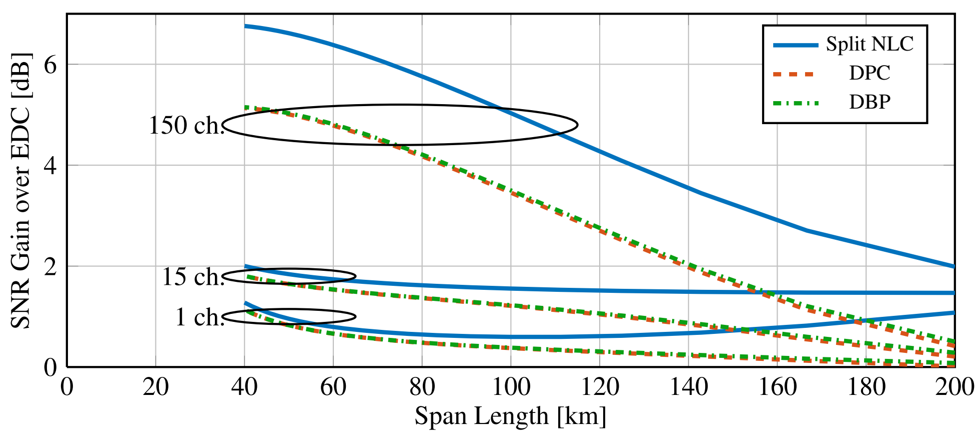

Fig. 4. Split NLC performance at 10000 km for different span lengths and number of compensated channels.

begins to dominate at large distances, the one span equivalent reduction in this term due to DPC becomes negligible. As can be readily seen from the summary in Fig. 3(b), for the case of Split NLC, an additional SNR gain of 0.2 dB is observed for single channel NLC after a transmission distance of 10000 km. In absolute terms, the NLC gain increases from 0.4 dB for conventional DBP, to 0.6 dB for Split DBP. This is because the performance of Split NLC versus DBP increases at long distances as the signal-ASE term becomes increasingly significant with the accumulation of ASE. (Note that a similar effect would be observed for shorter transmission distances provided similar accumulated ASE, for example due to high noise figure amplifiers or a larger fiber attenuation coefficient.) As is clear from Fig. 2(b), three channels would need to be simultaneously compensated using DBP in order to achieve the same gain as single channel Split NLC; greatly increasing the signal processing complexity.

Similarly, given the performance dependence of Split NLC on the signal-ASE interaction, we investigated how span length affected SNR gain when considering a limited NLC bandwidth

(Fig. 4) for a transmission distance of 10000 km. For DPC and DBP, performance monotonically decreases with span length for all NLC bandwidths. There is very little performance difference between DPC and DBP, for all span lengths, and the mitigation of the additional signal-ASE interaction in systems with long spans is not a feature of these algorithms. In contrast to the results for DPC and DBP, SNR gain increased at long span lengths for Split NLC when $B_{NLC} \ll B$. Further, a general trend can be observed; as the NLC bandwidth is increased, the span length at which Split NLC significantly outperforms DPC and DBP decreases.

4. Considerations for practical implementations of Split NLC

A key conclusion from the preceding results is that Split NLC offers equal or greater performance versus both DBP and DPC. Notwithstanding the significant implication for the design of NLC algorithms in general, the above analysis of (1) assumes an idealised transmission system with only one source of random noise (ASE), and the consequent stochastic process (nonlinear signal-ASE interactions). Practical systems are inherently limited by other noise sources, of which finite back-to-back SNR [1], equalization enhanced phase noise (EEPN) [19, 31, 32], and polarization mode dispersion (PMD) [7, 8, 21, 33] are the most significant when considering NLC performance. The following subsections explore the validity of the conclusions by discussing the impact of each noise source, with particular attention given to implications for the algorithms discussed herein.

4.1. Finite back-to-back SNR

The upper limit on the available SNR in a coherent optical transmission system, in the absence of nonlinear impairments, is bounded by the transceiver subsystems [1], mainly due to DAC and ADC quantization noise and timing jitter. In a realistic optical transmission system the received SNR, ($\mathrm{SNR_{TOT}}$), includes different, uncorrelated noise components as [34]

$$\frac{1}{SNR_{TOT}} = \frac{1}{SNR_{TR}} + \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NLI}}, \tag{5}$$

where, $\mathrm{SNR_{TR}}$ is the maximum SNR that can be achieved in the transmission system in the absence of NLI and ASE noise, which can be experimentally measured in a back-to-back configuration without ASE noise loading. The $\mathrm{SNR_{ASE}}$ accounts for the amplifier spontaneous emission noise and $\mathrm{SNR_{NLI}}$ accounts for the nonlinear noise components related to the fiber link.

At short transmission distances, the $\mathrm{SNR_{TR}}$ introduces the predominant source of noise in the system [34]. Thus, systems with finite SNR generally see limited digital NLC performance at short transmission distances, where the link SNR is relatively high compared to transceiver noise sources (see, e.g., [23]). At longer transmission distances, the effect of $\mathrm{SNR_{TR}}$ becomes much less significant, and the system performance is dominated by the accumulation of ASE and and NLI. The exact transmission distance where this difference occurs is clearly dependent on the value of the back-to-back SNR.

What are the implications of finite SNR for Split NLC? For shorter transmission distances, as shown in Fig. 2(a), Split NLC would still be beneficial when considering full field NLC, but the SNR gain over DBP or DPC will be smaller than for an idealised system. At longer transmission distances, as illustrated in Fig. 2(b), the performance is dominated by the accumulation of ASE, and the relative advantage of Split NLC would remain.

4.2. Equalization enhanced phase noise

EEPN arises due to the interaction between laser phase noise and the digital dispersion compensating filter; a fundamental aspect of all the algorithms discussed herein. If dispersion compensation is applied at the receiver, then the coherence of the local oscillator laser determines the degradation in performance due to EEPN, whereas the transmitter laser coherence determines the impairments generated by EEPN for transmitter-side dispersion compensation. For reasonable laser linewidths (approximately 100 kHz), the impact of EEPN on central channel performance has been shown to be negligible after NLC for 9×32 GBd DBP [19]. However, as EEPN increases with the bandwidth of the dispersion compensating filter [31] this may have significance for the wide bandwidth NLC results presented in this paper.

It should be noted that the performance degradation due to EEPN is not fundamental, as laser phase noise reduction and digital coherence enhancement (DCE) techniques have previously been shown to reduce the impact of EEPN. At the receiver, DCE is easily implemented using a secondary self-coherent receiver, to measure the local oscillator phase noise, and feed-forward DSP [35]. DCE is impractical to implement for the transmit laser, so laser phase noise reduction is typically implemented using feedforward filtering in the optical domain [36]. Ostensibly, the challenge of the optical domain technique is a key disadvantage for any NLC requiring transmitter-side processing, however the requirement of a secondary receiver (albeit at low sample rates) means DCE is also a relatively complex technique. Nevertheless, in the context of the present investigation, the validity of neglecting EEPN is not in question, as techniques exist for its mitigation.

Finally, assuming that laser phase noise remains both significant and uncompensated, what are the EEPN implications for Split NLC? In contrast to the superlinear scaling of the signal-ASE nonlinear noise coefficient, ξ, given in (4), to first order EEPN has been shown to scale linearly with distance. A trivial modification to [31, Eq. 37] yields the expression for the resulting noise variance due to EEPN.

$$\sigma^2_{EEPN} \propto DB(L_{pre} f_{Sig,3dB} + L_{post} f_{LO,3dB}), \tag{6}$$

where D is the dispersion parameter, B is the bandwidth of the dispersion compensating filter, L_{pre} and L_{post} are the dispersive fiber lengths pre/post-compensated, respectively, and $f_{Sig,3dB}$ and $f_{LO,3dB}$ are the 3 dB laser linewidths of the transmitter and local oscillator lasers, respectively. Evidence from numerical simulations shows that this linear trend holds for systems employing NLC [19]. Thus, under the reasonable assumption that $f_{Sig,3dB} = f_{LO,3dB}$, this indicates that DBP, DPC, and Split NLC would all see an equivalent impairment from EEPN, albeit relatively small for most realistic transmission systems.

4.3. Polarization mode dispersion

PMD is an apparently unavoidable physical phenomenon in optical fiber transmission. The effectively stochastic nature of PMD has been shown to limit the efficacy of NLC [7, 8, 21, 33]; in particular, PMD limits the bandwidth over which nonlinearity can be effectively compensated.

Split NLC divides the nonlinear compensation of the link into two, and is thus analytically comparable to mid-span optical phase conjugation (OPC). An analysis of the efficacy of NLC made for OPC introduced a nonlinearity compensation efficiency parameter [37, Eq. 2], which includes the effect of PMD. Split NLC can be incorporated into this analysis by analogy with the single OPC scenario. When using a single OPC per transmission link, both the nonlinearity mitigation and the accumulation of average differential group delay (DGD) are divided. For OPC, this division was shown to be mathematically equivalent to reducing NLI to that of a system with the PMD coefficient reduced by a factor of $\sqrt{2}$ versus the equivalent system employing DBP or DPC. Observing the symmetry between OPC and Split NLC, a similar effect is anticipated, which would enable nonlinearity mitigation at wider signal bandwidths and, therefore, enhanced NLC performance, overall.

It should be noted for completeness that PMD, although time-variant, is not truly a stochastic process, and knowledge of the DGD of each span of the transmission link can be used to improve the performance of NLC [8]. Directly monitoring the DGD is challenging, and to date has not been demonstrated. However, the total DGD accumulated over the link can be obtained from the tap weights of the adaptive equalizer at the receiver [38], and this information has been shown to be effective at mitigating the impact of PMD when incorporated into the DBP algorithm [20, 39]. Unfortunately, information obtained from equalizer tap weights is not available at the transmitter, so innovative experimental methods will need to be explored to implement PMD mitigation in either DPC or Split NLC.

5. Conclusions

Using a theoretical model for signal-to-noise ratio after wide bandwidth optical fiber transmission, the performance of Split NLC was evaluated relative to transmitter-side (DPC) or receiver-side (DBP) digital nonlinearity compensation. Although it was previously shown theoretically, and verified by numerical simulations, that Split NLC provides more than 1.5 dB SNR gain over DBP, the implications of this technique for a practical system had never been discussed. Split NLC, an equal division of digital NLC between transmitter and receiver, was shown to provide equal or greater performance when compared with DPC and DBP, in all scenarios investigated, regardless of the NLC bandwidth. Notably, for single channel NLC in an ultra-long haul scenario, Split NLC increased the SNR gain by 50% versus DBP. Further, the implications of realistic link parameters were highlighted, and the potential advantage of Split NLC in links impaired by PMD was discussed. Given that the computational complexity requirements are equal to the previously proposed algorithms, these performance advantages form a compelling argument for using Split NLC in all links employing digital NLC.

Funding

This work was funded by United Kingdom (UK) Engineering and Physical Sciences Research Council (EPSRC) Programme Grant UNLOC (UNLocking the capacity of Optical Communications), EP/J017582/1. This work was also supported by the Royal Academy of Engineering under the Research Fellowships scheme.

Acknowledgments

The authors wish to thank Dr. Tianhua Xu for fruitful discussions and advice on the implications of EEPN for transmission systems employing NLC.