

Various Nonlinearity Mitigation Techniques employing Optical and Electronic Approaches

Danish Rafique and Andrew D. Ellis

Abstract—In this letter we directly compare digital back-propagation (DBP) with spectral-inversion (SI) both with and without symmetry correction via dispersive chirping, and numerically demonstrate that pre-dispersed SI outperforms traditional SI, and approaches the performance of computationally exhaustive ideal DBP. Furthermore, we propose for the first time a novel practical scheme employing pre-dispersed SI to compensate the bulk of channel nonlinearities, and DBP to accommodate the residual penalties due to varying SI location, with pre-dispersed SI ubiquitously employed along the transmission link with <0.5 dB penalty. Our results also show that pre-dispersed SI enables partial compensation of cross-phase modulation effects, increasing the transmission reach by x2.

Index Terms—Kerr nonlinearity, network design

I. INTRODUCTION

Higher bit-rates per channel require the deployment of high-order modulation formats [1] with increased required optical signal-to-noise ratio, leading to increased channel nonlinearities. Dispersion management was initially proposed to suppress the impact of nonlinearity [2]. Although this technique is beneficial, it enforces severe limitations on link design. Compensation of fibre impairments based on phase conjugation or spectral inversion (SI) was also proposed [3-5], however, although SI has large bandwidth capabilities, it necessitates precise positioning (mid-link placement) and symmetric link design (e.g., distributed Raman amplification, etc.). Also, electronic mitigation of nonlinear impairments using digital back-propagation (DBP) has been applied to the compensation of channel nonlinearities [6]. However, the complexity of DBP is currently exorbitant due to ultra-wide bandwidth requirements, significantly high number of required steps per link, and the requirement of prior knowledge of fibre span configuration. Recent efforts to simplify single channel DBP [7, 8] show interesting prospects; however they may only be realistically applied for only a few spans before exhausting the computational resources.

In this letter, we directly compare various receiver-based electronic compensation (dispersion compensation and multi-precision digital back-propagation) and spectral inversion (uncompensated and pre-dispersed) techniques, in a coherently-detected 28 Gbaud polarization-multiplexed

quadrature amplitude modulation (PM-64QAM) transmission. We show that pre-dispersed SI (PSI) applied only once, not necessarily near the centre of the link outperforms traditional spectral inversion, and enables transmission performance equivalent to computationally extensive full-precision DBP (40 steps per span), where the placement accuracy of pre-dispersed SI has been validated up to 5 spans with less than 0.5 dB penalty. This is ensured by compensating residual penalties due to pre-dispersed SI dislocation by employing DBP for the remaining non-symmetrised spans, enabling significant reduction in required DBP stages. Furthermore, we establish that in a wavelength-division multiplexed (WDM) transmission, PSI enables x2 increase in reach.

II. TRANSMISSION SETUP

The transmission setup consisted of either one or nine 28 Gbaud PM-64QAM transmitters, an un-compensated link, and a coherent receiver (Fig. 1). The details of the setup can be found in [9], with a laser line width of 5 kHz. The signal was propagated over standard single mode fibre (SSMF) link with $N \times 80$ km spans and single-stage erbium doped fibre amplifiers. The fibre had attenuation of 0.2 dB/km, dispersion of 20 ps/nm/km, and a nonlinearity coefficient (γ) of 1.5/W/km. Each amplifier stage was modelled with a 4.5 dB noise figure. At the coherent receiver the signals were pre-amplified, filtered with a 50 GHz 3rd order Gaussian filter, coherently-detected and sampled at 2 samples/symbol. Transmission impairments were compensated using three different techniques, SI (and PSI), DBP, and electronic dispersion compensation (EDC).

1) Firstly by using SI: PM-64QAM channel was spectrally inverted at an offset from the middle of the link (where offset varied from 0 to 5 spans). In order to study the performance limits of the scheme, ideal SI was implemented by reversing the sign of the imaginary part of the signal. Note that optical [4] and electrical [10] implementations with sufficiently low penalties have already been reported. For pre-dispersed SI, a length of dispersion compensating fibre (DCF) equivalent to a dispersion of amplifier spacing (L_{amp}) - effective length (L_{eff}) of SSMF was applied (-20×58 ps/nm). The effect of the added DCF is that of modifying the value of accumulated dispersion exhibited by the pulses during propagation along the nonlinear regions downstream of the SI [5]. Note that an additional DCF must be inserted at the end of the link, or electronic compensation of additional dispersion can be applied [9]. We can see from Fig. 2 that for a conventional uncompensated map, the regions of high nonlinearity correspond to different accumulated dispersion on either side of standard SI. Whilst,

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The authors are with the Photonic Systems Group, Tyndall National Institute and Department of Physics (A.D. Ellis) / Electrical and Electronics Engineering (D. Rafique), University College Cork, Dyke Parade, Prospect Row, Cork, Ireland (e-mail: danish.rafique@tyndall.ie).

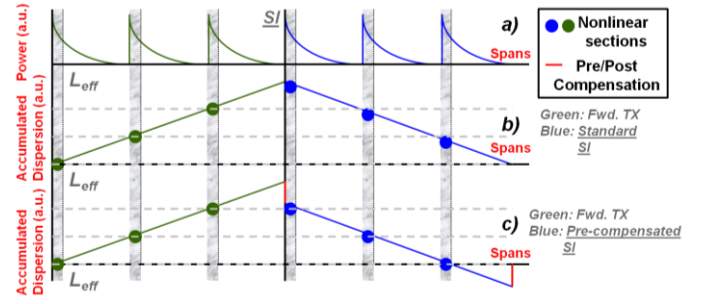
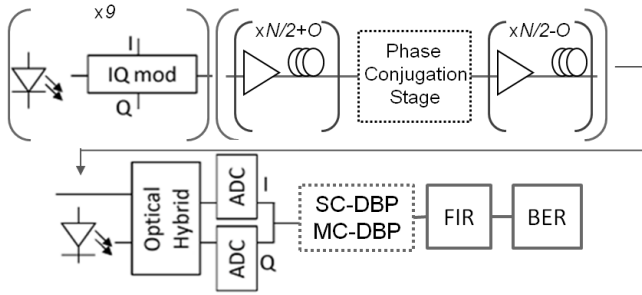


Fig. 1. Left: Simulation setup for 28 Gbaud PM-64QAM transmission. N : Number of spans, O : Offset for SI stage (0 to 5). IQ: in-phase, quadrature, ADC: Analog to digital, BER: Bit-error rate

Fig. 2. Right: Graphical representation for an uncompensated map showing, a) Optical power profile, b) Accumulated dispersion with standard SI, and c) Accumulated dispersion with pre-compensated SI, as a function of number of spans. Solid circles represent regions of high nonlinearity.

the addition of a small piece of DCF applying compensation for $(L_{\text{amp}} - L_{\text{eff}})$ ensures that nonlinear effects occur for similar ranges of dispersion.

2) In the second case, at the receiver electronic compensation was applied via digital back-propagation, numerically implemented by split-step Fourier method solution of the nonlinear Schrödinger equation. Unless mentioned otherwise, the step-size was fixed to 40 steps per span (ideal). In the case where pre-dispersed SI was applied with an offset from the centre of the link, we employed a simplified algorithm [7] for the remaining links (offset $\times 2$), with number of steps varying from 1 step/span to 4 steps/span.

3) Thirdly, EDC was employed using finite impulse response (FIR) filters (adapted using least mean square algorithm). Note that for the WDM transmission, both single-channel (SC) and multi-channel (MC) pre-dispersed SI and DBP were employed. In all cases, polarization de-multiplexing and residual dispersion compensation was performed using 13 tap FIR filters, followed by carrier phase recovery. Finally, the symbol decisions were made, and the performance assessed by direct error counting (converted into Q-factor (Q)). All the numerical simulations were carried out using VPItransmissionMaker v8.6, and MATLAB v7.10.

III. RESULTS AND DISCUSSIONS

Fig. 3 depicts the calculated Q as a function of launch power for 24 spans (1,920 km) transmission of single-channel 28 Gbaud PM-64QAM after EDC, standard SI, pre-dispersed SI

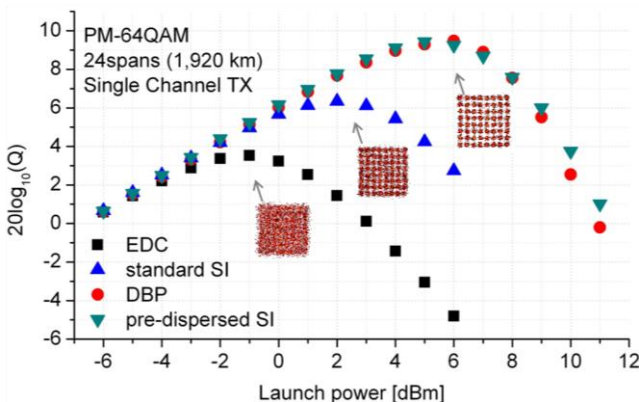


Fig. 3. Q as a function of launch power for 28 Gbaud PM-64QAM under various nonlinear compensation techniques. EDC (squares), Standard SI (up triangles), DBP (down-triangles), Pre-compensated SI (circles). Inset show constellation plots at optimum launch powers. TX: Transmission

and DBP. At lower launch powers, the system is noise-limited and Q of all approaches overlap. As we increase the launch power, different approaches demonstrate different optimum launch power, reflecting their dissimilar nonlinear compensation effects. As expected, both forms of SI outperform EDC by at least 2.5 dB. Most notably, enhancing the accuracy of standard SI by employing pre-dispersed SI enables the performance equivalent to that of ideal 40 steps per span DBP. Note that the intrinsic requirement of symmetrised power profile for standard SI can be relaxed by employing pre-dispersed SI technique, leading to a realistic application of SI in lumped amplification systems. Also, for an uncompensated map, symmetrising highly nonlinear regimes is sufficient to enable full compensation of deterministic fibre impairments with the addition of a single spectral inversion device (optical [4] or electrical [10]), compared to electronic signal processing based compensation of fibre nonlinearity, which is still impractical due to substantial requirements on receiver and DBP stages. More details in [11].

Another major concern regarding the practicality of SI techniques is the obscurity in placing the SI device exactly in the middle of the link. Here, we address this issue by evaluating the performance of pre-dispersed SI with various span offset relative to the centre of the link. Fig. 4 plots the Q as a function of span offset from the centre of the transmission link for PM-64QAM after 1,920 km. As expected, the performance degrades significantly as the offset is increased due to significantly uncompensated fibre nonlinearity after pre-dispersed SI. In order to compensate the residual channel nonlinearities, we employ both ideal and simplified DBP for the asymmetric spans, e.g. if SI is offset by two spans, one needs DBP worth four spans to get full nonlinear compensation with performance equivalent to mid-link placement of SI or ideal DBP for the entire link. One may also note that when simplified DBP is employed, the performance improves with the number of computational steps, and 4 steps/span enable performance within 0.5 dB of ideal DBP based pre-dispersed SI, and for smaller offsets, our hybrid solution outperforms simplified DBP employing 4 steps per span. Also, note that ideal DBP (40) on its own performs better than PSI(offset)+DBP(40). This due to the inherent first-order approximation, considered for PSI, of nonlinear impairments dominating within the effective length. Also, when PSI(offset) is employed, the link is asymmetric, and DBP(40) can only partially compensate for that (residual spans). Note that the benefit from this hybrid approach is

scalable to longer distances, and one might ascertain greater benefit for modulation formats supporting longer reach.

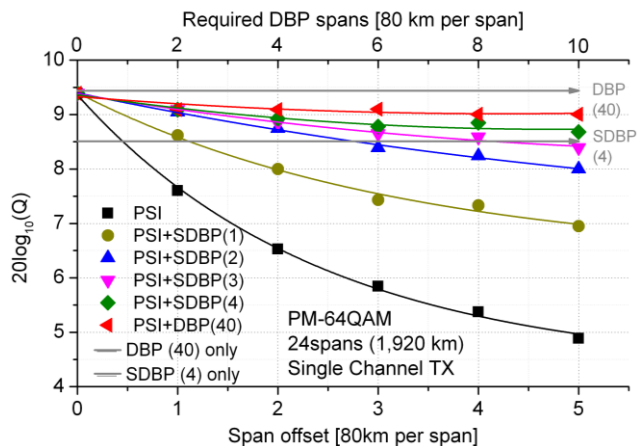


Fig. 4. Q versus span offset from centre of the link for 28 Gbaud PM-64QAM after 1,920 km (24 spans). Pre-dispersed SI (PSI) only (squares), PSI + simplified DBP(1) (circles), PSI + simplified DBP(2) (up-triangles), PSI + simplified DBP(3) (down-triangles), PSI + simplified DBP(4) (diamonds), PSI + DBP(40) (left-triangles). () represent number of step/span.

Finally, in order to determine the maximum performance with electronic compensation techniques, we established various transmission regimes where EDC, single-channel DBP (SC-DBP), single-channel pre-dispersed SI (SC-PSI), multi-channel pre-dispersed SI, and multi-channel DBP may be successfully used (Fig. 5), where each data point was taken from a plot, such as Fig. 3, at optimum launch power. It can be seen that the SC pre-dispersed SI enables full compensation of intra-channel nonlinear impairments, and enables performance equivalent to that of full-precision SC-DBP. The ultimate performance improvements are nevertheless enabled by rather impractical multi-channel DBP, however when wide band pre-dispersed SI is employed, cross-phase modulation (XPM) can be partially compensated. Note that only fractional XPM compensation is enabled since the neighboring channels walk-off the test-channel, which is not accounted for in pre-dispersed SI (optimum pre-dispersion is given by the dispersion length (walk-off length) for the nonlinearity to be compensated, however in this case, we symmetrise the intra-channel nonlinearity and therefore full compensation of XPM cannot be simultaneously achieved using the implementation in this paper). Nonetheless, one may still appreciate the $\sim x2$ improvement in transmission reach enabled by XPM compensation via pre-dispersed SI. Fig. 5 (inset) shows the impact of varying pre-dispersion, emulating the impact of dispersion slope (neglected in this study), and it can be seen that impact is negligible, consistent with previous results [12].

IV. CONCLUSION

We have proposed various solutions to compensate channel nonlinearities, employing diverse nonlinearity compensation techniques. It has been numerically demonstrated that transmission performance equivalent to ideal DBP can be attained with pre-compensated SI, overcoming the asymmetric power profile barrier. Furthermore, the practical utility of SI based systems is made possible by relaxing the requirement on mid-link placement of the SI device by ~ 5 spans with <0.5 dB

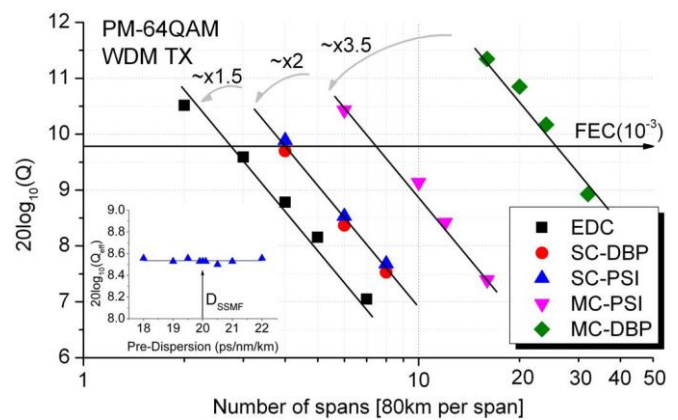


Fig. 5. Q versus transmission distance for nine-channel 28 Gbaud PM-64QAM, employing EDC (square), SC-DBP (circle), SC pre-dispersed SI (up-triangle), multi-channel pre-dispersed SI (down-triangle), and multi-channel DBP (diamond). Inset shows amount of pre-dispersion as a function of Q for SC-PSI (6 spans). FEC: Forward error correction

penalty, and compensating the residual nonlinearities by employing DBP for remaining asymmetric spans only. Finally our results suggest that pre-compensated spectral inversion also enables partial compensation of inter-channel nonlinear effects, further increasing the transmission reach by a factor of ~ 2 . We believe that the proposed scheme is a substantive step towards nonlinearity compensation for future networks (compared to DBP alone) since it essentially enables nonlinearity mitigation with circuit stages less than an order of magnitude to that of dispersion compensation alone.

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