LOW COMPLEXITY BACK-PROPAGATION FOR UPGRADING LEGACY SUBMARINE SYSTEMS

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Abstract: Capacity expansion of existing submarine cables is a very active topic in the submarine cable industry, both from a technical and commercial perspective. As new transmission technologies are proposed (such as digital coherent 100G), cable owners are demanding solutions to integrate such high-speed wavelengths into their existing networks. This paper analyses some of physical challenges in expanding existing infrastructure with new transmission technologies. In particular, the limitations imposed by fiber nonlinearity are analysed in the context of capacity expansion of legacy cable systems. In order to overcome the nonlinearity limit, novel techniques of nonlinearity compensation are introduced to specifically increase the transmission performance of digital-coherent high-speed transponders destined to expand legacy cable capacity.

1 INTRODUCTION

The capacity expansion of existing legacy submarine systems is attracting significant attention nowadays. With the advent of digital-coherent technologies, high data-rate 40G/100G channels will be deployed in new submarine cable systems. In addition, the increased spectral efficiency of 40G/100G DP-QPSK transponders opens the possibility of upgrading legacy submarine cable systems even beyond their design maximum capacity. Legacy submarine systems employ negative dispersion fiber to support long-haul transmission of 2.5G/10G intensity-modulated signals. These tightly-compensated maps eventually enhance intra- and inter-channel nonlinear effects such as self-phase modulation (SPM) or cross-phase modulation (XPM). As a consequence, a number of submarine legacy systems cannot be upgraded with DP-QPSK transponders, which present a higher sensitivity to nonlinear distortions. Nonlinearity compensation methods based on digital signal processing (DSP) have been proposed during the past years in order to increase the performance of digital coherent transmission systems. The most effective and comprehensive method to compensate fiber nonlinearity is the so-called digital back-propagation (DBP) method [1,2]. Although effective, DBP still requires large DSP complexity which makes difficult its implementation in current digital processors [3]. In this paper, we present a new DBP algorithm specifically designed to increase system performance of digital-coherent signals in submarine legacy systems. By compensating intra-channel XPM together with an equivalent link approach for the dispersion map, the number of DBP stages could be significantly reduced while still preserving a substantial increase of system performance. This new technique could be used to increase the number of legacy submarine cable systems that can support 40G/100G DP-QPSK upgrades.

2 NONLINEARITY COMPENSATION BY DIGITAL BACKPROPAGATION

Nonlinearity compensation (NLC) is a technique that has been proposed to combat the detrimental effects of fiber nonlinearity in optical transmission. Nonlinear effects could be of intra-channel nature (Self-phase modulation or SPM) or inter-channel nature (Cross-phase modulation or XPM and Four-Wave Mixing or FMW). These effects impose a serious limitation both in terms of transmission reach and system capacity.

In particular, nonlinear effects in legacy cable systems significantly affect the transmission performance of modern systems based on polarization multiplexed QPSK modulation and digital-coherent detection. However, in contrast to analog-direct receivers, current digital-coherent detection enables the correction of transmission impairments such as dispersion and fiber nonlinearity. Such impairment compensation is done using powerful digital-signal processing in high-speed microchips.

Although the compensation of chromatic dispersion is currently available in commercial digital-coherent transponders, the compensation of fiber nonlinearity still presents severe challenges in terms of DSP complexity. Therefore, it is of utmost importance to develop efficient algorithms for NLC so current DSP processors can support the algorithm complexity.

2.1 Equivalent link for reduced complexity back-propagation

One of the most effective methods for nonlinearity compensation is the so-called digital back-propagation (DBP) method. This method consists on implementing the propagation equations of the fiber but now, with negative parameters of dispersion, loss and fiber nonlinearity. In other words, the signal is back-propagated so the distortion induced by the combined effect of chromatic dispersion and nonlinearity can be, in theory, completely removed. The implementation of such propagation equations, namely the Nonlinear Schrodinger Equation (NLSE), in the digital domain has to be done efficiently and with the lowest possible complexity.

In order to perform DBP, the link parameters have to the known and introduced into the back-propagation equations. Since the NLSE does not have an analytical solution, multiple stages have to be used to solve it. Typically, the amount of stages required for DBP scales with the pulse spreading, the variations of the fiber properties and the DSP complexity.

One way to significantly reduce the complexity of back-propagation is to reduce the number of DBP stages. To do so, an *equivalent link* for DBP can be used [4]. This equivalent link is able to reverse the nonlinearity distortion accumulated throughout the real-link by using z-invariant parameters. In consequence, the number of stages required for DBP is significantly reduced as it is shown in Fig. 1.

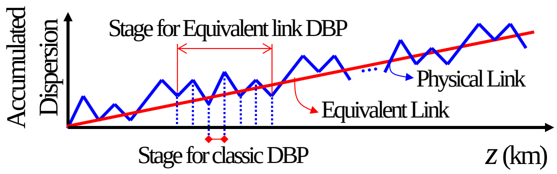

Fig. 1: Equivalent link DBP concept showing the reduced number of stages required for DBP when equivalent link is used.

Intra-channel XPM compensation for single step back-propagation

The equivalent link approach is a very effective technique to reduce the complexity of back-propagation in legacy links composed of NZ-DSF, which are the ones that carry the majority of the capacity nowadays. However, as shown in fig. 1 it is still necessary to use several steps to achieve optimum performance. As each steps involves a pair of FFT operations, it is still challenging for current DSP processors to implement multi-step algorithms. One technique to reduce the number of steps is to compensate intra-channel XPM (*i*XPM). By slicing the spectrum of the signal into sub-bands, each sub-band can be back-propagated independently only considering the XPM interaction between the sub-bands (i.e. neglecting *i*FWM contributions). Because of the reduced bandwidth of the sub-bands, the number of DBP stages could be dramatically reduced even to the single-stage level. First, the incoming signal is converted to the frequency domain and the spectrum is sliced into sub-bands. Then, chromatic dispersion compensation (CDC) is applied to each sub-band. After CDC, walk-off filtering is applied to each sub-band signal power and the *i*XPM contribution is computed for each sub-band. Figure 2 shows a schematic of the proposed method where m is the number of stages and n is the number of sub-bands.

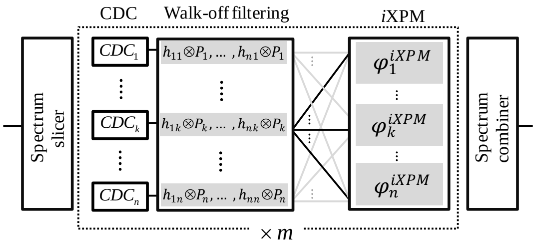

Fig. 2: Schematic diagram of the *i*XPM back-propagation algorithm. Extension to two polarization case is straight-forward.

The walk-off factorization formulation can be found in [5] for inter-channel XPM compensation. The extension to intra-channel XPM is straightforward. The dispersive walk-off per stage and the dispersion compensation per stage are determined by using the equivalent link approach introduced in the previous section.

3 EXPERIMENTAL RESULTS AND DISCUSSION

The experimental test-bed consists of a 3400 km straight-line link with an average span length of 46 km of NZ-DSF and SMF. On average, SMF is located every 6-7 spans of NZ-DSF. The output power of the amplifier is +12.5dBm. These dispersion maps were typically deployed in the late nineties for long-haul 10G transmission. In this experiment, DP-QPSK channels (8×127 Gb/s) are located between 1557.77nm to 1560.61nm at 50GHz spacing for capacity upgrade emulation. Average dispersion of the NZ-DSF spans is -2.3 ps/km/nm whereas dispersion of SMF is 19.0 ps/km/nm. The experimental dispersion map is shown in Fig. 3, together with the optimum equivalent map.

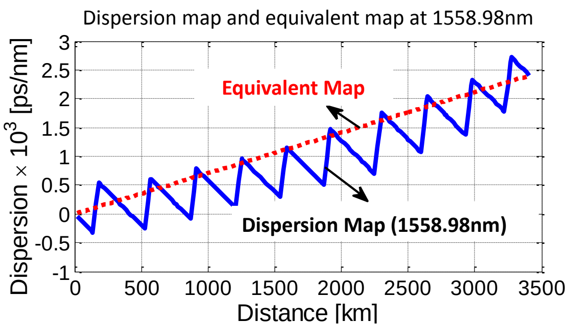

Fig. 3: Physical dispersion map and equivalent link for DBP.

To evaluate the proposed *i*XPM compensation method, experimental results were obtained using the same testbed as described in the previous section. Fig. 3 shows the transmission results with back-propagation based on *i*XPM compensation. Two main parameters are considered in the analysis of the method, namely: number of sub-bands, n and number of back-propagation stages, m.

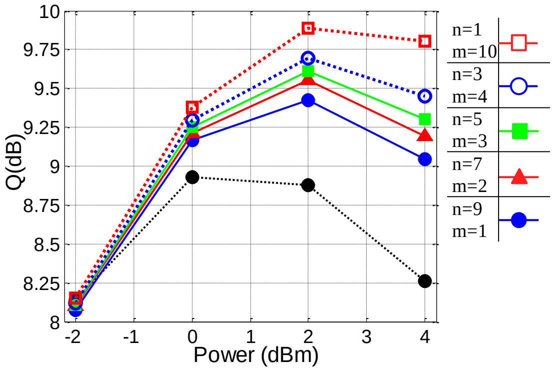

Fig. 4: Performance results as a function of optical power for different configurations of number of sub-bands, *n* and number of steps *m*.

From the results, a trade-off between the number of sub-bands and the number of stages can be clearly observed. Maximum performance is obtained at n=1, i.e. no spectral slicing, for a number of stages larger than 6-7. This is an expected result because slicing-based *i*XPM back-propagation neglects the *i*FWM interaction. However, taking that interaction into account comes at the expense of more algorithmic stages. As the spectrum is sliced into sub-bands, the number of required stages for optimum performance is decreased, as shown in Fig. 5.

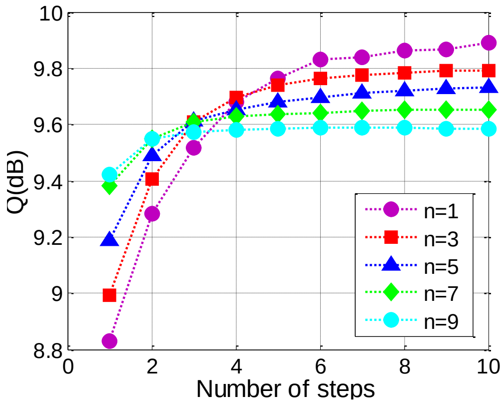

Fig. 5: Performance results as a function of the number of stages (steps).

For 9 sub-bands, almost 0.5 dB improvement is obtained at single-stage operation. This is, to our knowledge, the first back-propagation algorithm that is able to achieve improvement in a single stage (1 FFT/IFFT pair) operation.

Figure 6 shows the optimum number of sub-bands for a give number of stages. It can be seen that there is an optimum number of sub-bands for a given number of stages. Beyond that number, the effects of *i*FWM start to be important and the effectiveness of *i*XPM compensation begins to drop. Below that number, the dispersive effects per sub-band are too large for a single stage operation.

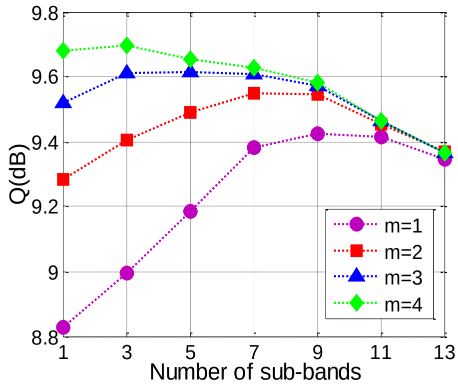

Fig. 6: Performance results as a function of the number of sub-bands.

In terms of implementation complexity, it is clear the benefit of the proposed *i*XPM in terms of reducing the number of stages. However, each stage additional complexity due to the walk-off filters. Due to the averaging nature of the walk-off, the implementation of such filter in the time-domain can be simplified to very few multipliers. In addition, this single stage algorithm could be also implemented in the transmitter side, by means of look-up-table operations. In this case, the discrete nature of the input signals could significantly reduce the system complexity.

CONCLUSION

A new back-propagation method based on *i*XPM compensation is presented. The method consists of three main elements: i.e., spectral slicing, *i*XPM compensation with walk-off filtering and equivalent dispersion map. This algorithm has the potential to perform single-stage nonlinearity compensation. A trade-off between the number of sub-bands and the algorithmic stages is analyzed. It is shown that an optimum number of sub-bands can be obtained for a given number of BP stages.

4 REFERENCES

[1] E. Ip and J. M. Kahn, "Compensation of Dispersion and Nonlinear Impairments Using Digital Backpropagation," J. Lightwave Technol. 26, 3416-3425 (2008)

[2] X. Li, X. Chen, G. Goldfarb, E. Mateo, I. Kim, F. Yaman, and G. Li, "Electronic post-compensation of WDM transmission impairments using coherent detection and digital signal processing," Opt. Express 16, 880-888 (2008)

[3] L. Li, Z. Tao, L. Dou, W. Yan, S. Oda, T. Tanimura, T. Hoshida, and J. C. Rasmussen, "Implementation Efficient Nonlinear Equalizer Based on Correlated Digital Backpropagation," OFC2011, paper OWW3 (2011)

[4] E. Mateo, M-F, Huang, F. Yaman, T. Wang, Y. Aono, T. Tajima, "Nonlinearity compensation using very-low complexity backward propagation in dispersion managed links," OFC2012, paper OTh3C (2012)

[5] E. Mateo, X. Zhou, and G. Li, "Improved digital backward propagation for the compensation of inter-channel nonlinear effects in polarization-multiplexed WDM systems," Opt. Express 19, 570-583 (2011)