The Impact of Phase Conjugation on the Nonlinear-Shannon Limit

The Difference Between Optical and Electrical Phase Conjugation

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***Abstract*—We show that optical and electrical phase conjugation enable effective nonlinear compensation, The impact of polarization mode dispersion and finite processing bandwidth on the ultimate limits are also considered.**

Keywords—Optical Fiber Communication, Fiber Nonlinear Optics

I. INTRODUCTION

The terms "nonlinear Shannon limit" [1] and "capacity crunch" [2] are increasingly used to suggest that the maximum data throughput of an optical fiber has been reached and that deployed systems are within sight of this limit respectively. Recent research has largely been focused on ability of digital signal processing (DSP) to reverse nonlinearity, and for optical phase conjugation (OPC) to do so for multiple channels simultaneously, with impressive numerical and experimental results. A particularly promising digital signal processing technique introduced recently involves transmitting a phase conjugate copy of the data [3] (or a subset of the data [4]) along with the signal. When re-conjugated and coherently added back to the signal improve the signal-to-noise ratio and can, in certain circumstances, compensate nonlinearity.

In this paper, we compare the relative merits of various nonlinearity compensation techniques based on phase conjugation, and investigate their potential to allow data throughputs beyond the nonlinear Shannon limit.

II. NONLINEAR SHANNON LIMITS

We consider a generalized format for the nonlinear Shannon limit, considering amplified spontaneous emission, inter-signal nonlinearity, and parametric noise amplification but neglecting signal depletion [5] effects. It is given by [6]:

$$SNR_{NL} \approx \frac{M_C P_S}{N \cdot P_{ASE} + N(\eta - \eta_C) P_S^3 + f_{SN}(N) \cdot \eta \cdot P_{ASE} P_S^2} \quad (1)$$

where P_S represents the signal power spectral density, M_C the number of simultaneously transmitted copies of the signal, N the number of spans, P_{ASE} the amplified spontaneous emission power spectral density generated by each span, η a coefficient of nonlinearity depending approximately logarithmically on the WDM signal bandwidth B_S (which should take into account spectral broadening during transmission), and η_C represents the efficiency of nonlinear compensation (NLC) and depends on the effective bandwidth of the nonlinear compensation system and non-deterministic signal decorrelation due to, for example, polarization mode dispersion (PMD). The form of η depends on the nonlinear model chosen, but this choice has little practical impact in this paper. Parametric noise amplification scales nonlinearly with length in a manner given by;

$$f_{SN}(N) \approx \left(\frac{N}{N_L} + N_L \sum_{n=1}^{\frac{N}{N_L}-1} n \right) \quad (2)$$

where $N_L = 1$ for DSP and 2 for mid link OPC. Whilst detailed models for η_C exist [5-7], we assume a simplified form comparing the effective compensation and signal bandwidth and the relative correlation bandwidths of the NLC and PMD. By heuristically assuming that only the spectrum which would pass a Lyott filter with the mean birefringence of the link correctly contributes to NLC, integration reveals that;

$$\frac{\eta_C}{\eta'} \approx \frac{CI\left(Min(B_C \sqrt{L}\sigma_P, \pi/2)\right) - CI\left(f_W \sqrt{L}\sigma_P\right)}{Log(B_s / f_W)} \quad (3)$$

where η' takes into account the difference between polarization multiplexed transmission with random orientation and with fixed orientation (the well know 8/9 factor), B_C is the effective bandwidth of the NLC, L the compensated length, σ_P the PMD parameter, f_W the nonlinear phase matching bandwidth and CI the Cosine Integral. We find agreement between Eqn. 3 and [7] for the parameter range of interest here.

III. IMPACT OF COMPENSATION TECHNIQUE

Optimizing the launch power in equation 1 assuming no parametric noise amplification ($f_{SN}=0$) gives the well-known nonlinear Shannon limit, whilst optimizing for ideal nonlinear compensation ($\eta_C = \eta$) gives a system by limited parametric noise amplification. It is straightforward to show that, in these ideal scenarios, compensation of nonlinearity should result in an increase in the signal to noise ratio after compensation, in

This work was supported in part by the UK EPSRC through grants EP/J017582/1 (UNLOC) and EP/L000091/1 (PEACE) the European Commission's 7th Framework Programme FP/2007-2013 grant 318415 (FOX-C) and The Royal Society under grant WM120035 (TEST).

978-1-4799-7468-9/15/$31.00 ©2015 Crown

dB, of 50% of the uncompensated signal to noise ratio, plus 2.6dB. This is shown by the solid points of Fig. 1, where the performance without NLC, phase conjugate pilots (PCP) and phase conjugate subcarrier coding (PCSC) [8] are compared (taking into account the 3dB difference between Q^2 and SNR for a QPSK signal). Theoretical lines are also shown, where η_C is used as a fitting parameter (~ two channels equivalent bandwidth). A significant increase in SNR is obtained from OPC, which may be understood from the increased bandwidth of the NLC and the additional 1.5dB predicted by Eqn. 2, governing parametrically amplified noise growth.

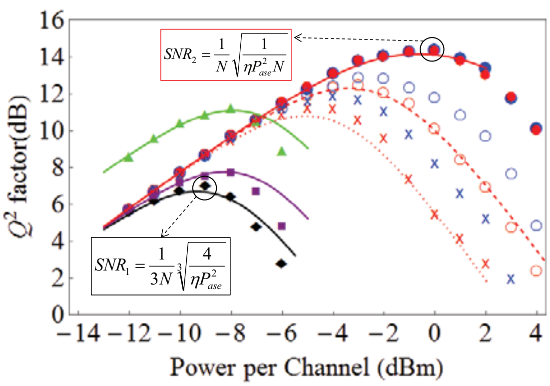

Fig. 1. Performance of a 7×15Gbaud QPSK Nyquist-spaced PDM WDM CO-OFDM transmission over a 50×80km with ideal Raman amplification showing no NLC (black), PCP (green), PCSC (purple), OPC (red) and OPC+PCSC (blue). OPC and OPC+PCSC with 0.1ps/√km (open symbols), and 0.2ps/√km (crosses) also shown. 50 fibre realisations used for PMD studies. Equations for optimum SNR shown as insets for convetnional transmission and transmission with OPC. Theoretical curve fitsshown for 0 ps/√km (solid), 0.1 ps/√km (dashed) and 0.2 ps/√km (dotted) PMD.

However, these benefits rely critically on the accuracy of the nonlinear compensation. This partly depends on the ADC performance and any DSP simplification, but is more fundamentally limited by the effective bandwidth of the NLC, and by PMD. The predictions of Eqn. 3 are compared against a second numerical simulation [9] in Fig. 2, where the NLC bandwidth is set to the bandwidth of 1, 3 and 5 channels for a PM-16QAM Nyquist WDM signal. Excellent agreement within 0.3dB is observed (with η including broadening of the WDM signal spectrum equal to the phase matching bandwidth f_w) and the majority of the benefit of NLC is retained for an achievable PMD coefficient of less than *0.1 ps/√km*. However Eqn. 3 is strongly dependent on the total signal bandwidth, and for a fully populated WDM system, the PMD coefficient should be below *10 fs/√km*. Furthermore, it is apparent that not all signal processing configurations may achieve the limit imposed by parametric noise amplification, especially if any portion of the spectrum is truncated. These restrictions would also apply equally to DSP and OPC techniques, but might not apply to the various forms of phase conjugate twin wave, since the two copies of the signal experience the similar nonlinear impairments, and the technique does not rely on excess receiver bandwidth, or on any particular PMD assumptions.

Considering the implications of the above suggests that the optimum NLC regime would incorporate phase conjugate coding to minimize the impact of PMD, along with wideband OPC to reduce parametric noise amplification. The potential interworking of these two techniques is shown in Fig.1. The simulated and theoretical (η used as a fitting parameter) impact of PMD on the OPC based system are shown to degrade the performance, however the combination of PCSC signals and an OPC link reduces the PMD penalty. In the absence of PMD, there is no performance degradation for the combined NLC.

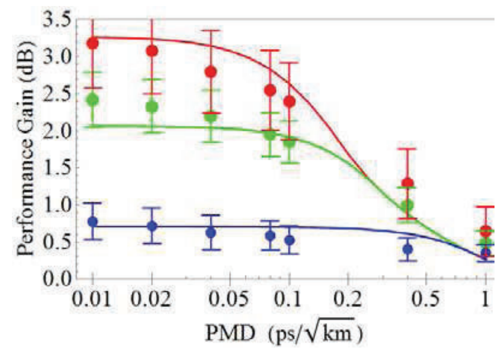

Fig. 2. Influence of PMD on the NLC gain of a 5x32 Gbaud dual polarisation 16QAM Nyquist WDM system over 40*80.17km spans with digital back propagation, showing (dots) simulated results [9] and (solid line) predictions of Eqn 3 for one (blue), three (green) and five (red) channel DBP. 10 fibre realisations were used for PMD studies. Error bars are 1.5 standard deviations.

IV. Conclusions

In this paper, we have analytically considered the fundamental limiting of features of nonlinear compensation (parametric noise amplification, bandwidth and PMD). We have argued that only OPC offers significant ability to resist parametric noise amplification and that some form of phase conjugate coding is required for operation on fibers with finite PMD. A combination of the two techniques should allow the throughput of a given system to be increased by 50%.

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