Impact of Optical Phase Conjugation on the Nonlinear Shannon Limit

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Abstract: Compensation of the detrimental impacts of nonlinearity on long haul wavelength division multiplexed system performance is discussed, and the difference between transmitter, receiver and in-line compensation analyzed. The impact of system imperfections is also outlined.
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1. Introduction

The perception of the nonlinear Shannon limit [1] is currently seen as preventing the continued smooth (exponential) increase of optical transmission throughput, resulting in a predicted capacity crunch [2]. The focus of the research community on these issues has resulted in specific international discussion meetings [e.g. 3] and even significant inducement prizes [4]. One of the earliest proposals to compensate for nonlinear impairments in an optical transmission system was the use of optical phase conjugation (OPC) [5,6]. In an OPC system, the entire signal is phase conjugated after a certain length of a transmission system. If the signal is then propagated through an identical length (subject to certain symmetry conditions) nonlinear effects and even-ordered dispersive effects are reversed. If the symmetry conditions are not met, then partial compensation of the impairments is still possible [7]. Following early work on direct detection systems [e.g. 8-10] which were severely constrained by nonlinearity, recent attention has focused on the digital signal processing capabilities enabled by nested Mach-Zehnder modulators [11] and digital coherent receivers [12]. However, as we approach the nonlinear Shannon limit there is renewed interest in the direct compensation of nonlinear impairments. In this paper, we review recent progress in the use of optical conjugation for the mitigation of nonlinear impairments in both serial and parallel configurations, and estimate the extent to which each technique may enable transmission beyond the nonlinear Shannon limit.

2. Parallel conjugated copies

Simulations have shown digital back propagation to be a useful technique [13], resulting in transmission performance limited by interactions between signal and noise [14] or by polarization mode dispersion [15]. However, implementation is complex, multiplying the digital equalizer complexity by several factors. This complexity increases rapidly if compensation over multiple channels is performed [16]. Through appropriate linear combination operations, it is possible to transmit two polarization multiplex signals and their phase conjugated copies over the same transmission line [17]. This so called Polarization Time Coding was shown through numerical simulations to be resistant to the nonlinear effect of polarization scattering. More recently this concept has been generalized and experimentally demonstrated using a single data channel and its conjugate copy [18-23]. The copy may be multiplexed in any available dimension, including polarization [18, 19], wavelength channel [20], time [21] and subcarrier frequency [22,23]. Ideally the signal and its conjugate copy would experience identical (or deterministically scaled) nonlinear impairments, and would accumulate statistically independent amplified spontaneous emission (ASE) noise. At the receiver, the conjugated copy is re-conjugated and added to the original signal. Since ASE noise is uncorrelated, but the two copies of the signal are correlated, the signal to noise ratio is increased by 3dB (this principle applies to an arbitrary number of copies). The anti-correlated nonlinear effects add destructively and the deterministic nonlinear impairments are in principle fully cancelled, leaving the system limited by parametric noise amplification [14-16]. This results in an increased signal to noise ratio of $1.8(snr_0)^{3/2}$, where snr_0 is the signal to noise ratio of one uncompensated copy, or 2.55 dB plus 50% of the original *snr* in dB [24]. 3dB of this improvement arises from sending the extra copy, effectively doubling the signal bandwidth. As a consequence of this effective bandwidth reduction, despite the attractively simple signal processing (a few additions and phase inversions), net benefit from this approach is only achieved for original signal to noise ratios below about 6 dB.

The number of systems where transmission of a conjugate copy enhances performance may clearly be improved by reducing the additional bandwidth required. This may be achieved by only transmitting one conjugate for every n^{th} data signal and, provided the nonlinear impairments are sufficiently identical as is the case for adjacent channels in an OFDM system, estimate the nonlinear impairment on other channels [22,23]. Clearly the nonlinear mitigation is somewhat less than conjugating every signal, but due to the reduced excess bandwidth net performance gains in the region of 1.5dB have been observed. A more straightforward approach is of course the conjugate coding of pairs of signals [25,26] fully generalizing the 2x2 MIMO approach of [17]. This approach maintains the full nonlinearity mitigation benefit, but loses the signal to noise ratio benefit of coherent superposition [27] available when only one signal and its conjugate are used. In this case the maximum potential signal-to-noise ratio gain is simply $0.9(snr_0)^{3/2}$, and benefits are observed for all uncompensated signal-to-noise ratios.

Transmitter configurations may be simplified by the use of four wave mixing devices to simultaneously generating all of the required conjugate copies [19,28]. At the receiver, a phase sensitive amplifier, which essentially interferometrically combines an input signal and idler (the signals conjugate copy), may be used to perform the required coherent addition [28,29], although pump phase locking is required [30]. By combining all-optical conjugate copy generation and receiver processing, the combined benefits of nonlinearity mitigation and reduced noise figure are simultaneously achieved [31], such that the signal to noise ratio gain over a conventional single channel system using phase insensitive amplifiers would approach $3.6(snr_0)^{3/2}$.

3. Serially generated conjugates

Alternatively, we can consider manipulating the signal in the transmission link using OPCs; this allows implementation using shared optical resources, full modulation format transparency and, more significantly, the disruption of parametric noise accumulation [14, 31]. Optimization of performance requires careful design to ensure symmetry in power profile and dispersion in each segment of the transmission link. The simplest configuration is to place an OPC in the middle of the transmission path [5-10]. This can lead to a *snr* gain of up to $1.27snr_0^{3/2}$ equivalent to a $1.17\ snr_0^{1/3}$ reach enhancement [37]). However for an EDFA only system mid-span placement leads to dispersion-power asymmetry [38] which needs to be compensated or ultra-flat Raman amplification used [32, 39]. Practical demonstrations of this have been reported with significant performance enhancements for WDM systems with reasonable transmission symmetry in power [32-34] and dispersion [35]. Nonlinearity compensation of a total bit rate 2.4Tbit/s using a single dual-band OPC allows a ~50% increase in reach for six simultaneously transmitted 400Gbit/s 16QAM super-channels with an 18% power asymmetry (75 km link length) over standard single mode fiber [37]. Transmission over dispersion shifted and flattened fiber, using Raman amplification and a single OPC has enabled a significant 3dB increase in the margin of a 2000 km 4×67.25 Gbaud-16QAM WDM system.

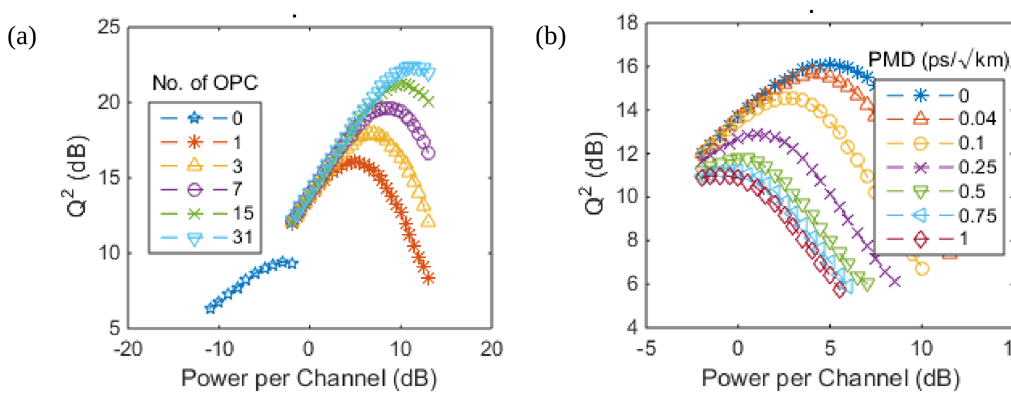

Fig. 1. 5 Channel 28 GBaud Nyquist PM-QPSK transmission over 32 x80 km of standard single mode fiber considering ideal OPC and Raman amplification using $10x2^{12}$ symbols. (a) Performance improvement achieved by disruption of parametric noise amplification by between one (red) and 31 (light blue) OPCs distributed symmetrically along the link, also shows uncompensated link (dark blue). (b) A single OPC system subject to statistical asymmetry induced by PMD, showing PMD free (blue), spun fiber (red triangle), typical fiber (orange) and various higher levels.

In order to provide greater performance benefits, multiple OPCs have been shown to increase the *snr* to $0.9(N_{OPC}+1)^{1/2}(snr_0)^{3/2}$, where N_{OPC} is the number of symmetrically deployed OPC [31]. The additional performance gain is due to the prevention of the quadratic growth of parametrically amplified noise**.** Cascadability of OPCs has been demonstrated using fiber based OPCs [34, 36]. Ten OPC operations (once every 600 km) enabled a net 2.5 dB increase in *snr* after accounting for an OSNR implementation penalty of ~2.4 dB [36] consistent with analytical predictions (4.5dB) [31]. The OSNR penalty may be normalized out using appropriate reference configurations [34] allowing an 8dB increase in the optimum launch power to be achieved. The 6.2 dB theoretical maximum increase in launch power, given by $1.17\ ((N_{OPC}+1)snr_0)^{1/2}$, is close to the observed value, although due to the OSNR performance of the loop the performance improvement was a modest 1dB (theoretically 4.9dB).

While power and dispersion symmetry can be predicted and controlled [38], statistical properties of using a real transmission link for signal and conjugate transmission will result in an unforeseeable asymmetry. This will limit the amount of non-linear compensation possible [37]. For a 200 GHz bandwidth 16QAM Nyquist WDM signal with ideal power and dispersion symmetry, a typical PMD coefficient of 0.1ps/√km would reduce the reach enhancement to only ~50%. PMD is also a significant restriction for the effectiveness of digital back propagation [16], which is also constrained by the available signal processing bandwidth [40]. To illustrate the disruption of parametric noise amplification and the effect of PMD and, we have numerically simulated, using VPI and Matlab, transmission of 5 Nyquist PM-QPSK channels over 2,560 km. Details of the DSP used are available in [31]. Fig. 1a shows performance when serially concatenated conjugations are performed along the transmission link, confirming the 7dB analytically predicted performance improvement for the use of 31 OPCs. Fig. 1b shows that the performance benefit is degraded by PMD. For typical low PMD fiber (0.1 ps/√km), there is a reduction in the performance gain of only 1.5 dB, but for large values of PMD the benefit of the OPC is almost completely eroded. The PMD penalty will increase with system bandwidth and will be a critical design parameter for future OPC based systems [37].

4. Conclusions.

We have outlined the potential benefits of conjugation (co-propagated and serially) to compensate deterministic non-linearity and so provide performance beyond the nonlinear Shannon limit. These benefits do not come without a cost; either in overhead, link design or DSP complexity; but these problems should not be insurmountable.

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