Challenges of Developing Non-linear Devices to Achieve the Linear Shannon Limit

(Invited)

M.E.McCarthy, S. Sygletos, N. Mac Suibhne, M. Tan, M.Stephens, I.D.Phillips, P.Harper, N.J.Doran, A.D.Ellis
Aston Institute of Photonics Technologies, Aston University, Birmingham, B4 7ET, UK
e-mail: m.mccarthy@aston.ac.uk

ABSTRACT
To achieve the Shannon Capacity Limit, we need to develop practical, effective and deployable non-linear devices to invert the non-linear effects of the transmission line. In this work, we will summarise the progress we are making to realise these, specifically looking at optical phase conjugation and phase regenerators as methods to improve non-linear tolerances.
Keywords: nonlinear optics; parametric amplification; optical phase conjugation; network capacity.

INTRODUCTION

Current state of the art digital signal processing (DSP) methods allow for intra-channel impairments such as chromatic dispersion and self-phase modulation effects to be compensated completely [1]. Along with amplified spontaneous emission (ASE), inter-channel Kerr effects will be the principal sources of impairments that limit the information capacity of an optical communication system. The Kerr effect induces random fluctuations in data channels which are related to the intensity of the neighbouring wavelength division multiplexed (WDM) channels. In order to compensate for the deterministic contributions of nonlinear channel noise and to realise systems that extend beyond the current nonlinear-Shannon limit [2]-[7], several techniques have been proposed to combat inter-channel nonlinear effects. Some of these techniques include digital back propagation (DBP) [8], mid-span phase conjugation (OPC) [9] and phase regenerators (PR) [10]. Here, we will examine the key challenges of achieving the potential maximum information spectral density (ISD) using each of these approaches in terms of power consumption; and for optical material based devices, we will comment on the specific technology limitations, the compatibility with multi-wavelength and high order modulation formats.

1. POWER CONSUMPTION

Considering the current necessity to reduce our carbon foot print and noting that 1-2% of the world's energy consumption [11] is estimated to be utilised by communications networks, any new technique should ideally provide a greater capacity per Watt than multiple parallel conventional (Erbium doped Amplifier (EDFA) based) systems. Figure 1(a) compares the maximum achievable information spectral density (ISD) of four proposed techniques mid-span OPC, DBP (over 50 GHz and the full field) and phase regeneration (every span) to a conventional EDFA based system assuming 80km spans and using the common form of the nonlinear-Shannon limit [12]. This figure clearly shows the advantages of using the proposed non-linear devices to increase capacity, with regeneration favoured for the longest spans and inter channel nonlinearity compensation offering the highest capacity for system lengths of up to around 1,000km.

In Figure 1(b), we approximate the power consumption for each transmission scheme to operate at an ISD of 16 b/s/Hz with a 5 THz spectrum fully loaded with Nyquist spaced 28 Gbaud channels, assuming operation at the maximum possible bit rate for the system technology and multiple spatial paths [13]. The technologies are immature so optimisation and power reduction is likely occur and is the subject of current investigation and investment for the baseline (high power EDFA) technology. Based on a survey of commercial MSAs and calculations in [14], we assume a transponder power consumption based on the level chromatic dispersion compensation required for 28 Gbaud PM-QPSK as is approximately 60W+7W/Mm. Commercial available WDM EDFAs for terrestrial systems are also commercially and have a typical power consumption of 15 W per amplifier per span. DBP power consumption is dominated by the additional CMOS processing which scales with the step size, assumed to be one step per fibre span and approximately 2 W per span for each channel. Full field DBP propagation is currently a vibrant area of algorithm optimisation so we leave the power estimation of this as an open question, noting simply that it is unlikely to be less than the power consumption of single channel DBP.

OPC and PSAs are dominated by the additional lasers and high power EDFA. As these components are not currently mass produced for the telecommunications industry, bench top power consumption for the components is assumed. This assumption is realistic for current market conditions, but greatly overestimates the fundamental power consumption for these devices. If the technology is favourable under this assumption, we expect a considerable reduction in power consumption as device volumes increase. A high power EDFA with output power up to 42 dBm consumes approximately 300 W and an external cavity laser (ECL), including cooling and control circuits, ~10 W. This work assumes two parallel OPC conjugators of 2.5 THz bandwidth each and that dispersion compensation is un-necessary or negligible in the transponders, offsetting the energy consumption of the OPC node itself. A PSA is assumed to be able to compensate *n* wavelengths and consist of high power EDFA and two ECLs.

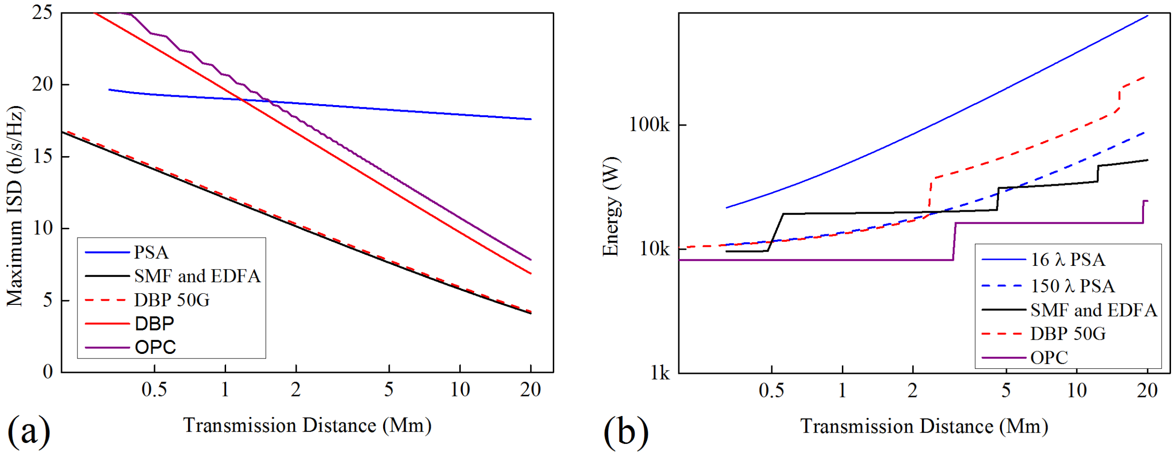

Figure 1 (a) Maximum achievable Information Spectral Density (ISD) vs distance for SMF and EDFA (black); Digital Back Propagation (red dashed 50 GHz bandwidth; solid full bandwidth); Optical Phase Conjugation (purple) and Regeneration (blue) (non-linear coefficient (γ) = 1.4/km; dispersion (D) = 16 ps/nm/km; n_{sp} = 1.58; and a total bandwidth of 5 THz) (b) Power Consumption for each transmission link for an ISD of 16 b/s/Hz (allowing parallel links when the maximum ISD is exceeded)

These graphs show that using a mid-span OPC for dispersion compensation alone the most attractive in terms of energy consumption at all span lengths, since the additional energy consumption of the OPC devices (640W) is more than offset by the DSP saving of 14 W per wavelength (2.5 kW in total). This is despite the pessimistic power consumption assumptions for this technology. Additionally, from Figure 1(a), that use of repeated optical regeneration is the only method that can provide an ISD of 16 b/s/Hz on a single fibre over 1000 km for a single fibre but to make it realistic from deployment, it must be able to regenerate modulation formats with similar complexity to polarisation multiplexed 256 QAM and to simultaneously process considerably more than 16 wavelengths per high power EDFA.

2. OPTICAL PHASE CONJUGATION CHALLENGES

Optical phase conjugation (OPC) [15]-[16], conceived as a technique to combat nonlinearity [9]originally gained interest as a method for dispersion compensation [17]-[19] but were over taken firstly by dispersion compensation fibres and then by electronic dispersion compensation. An OPC mirrors the optical signal spectrum at some point close to the mid-point of the transmission link such that the impairments of the first part of the transmission are undone by the second. Fibre based OPC is realised by utilising the Kerr effect in specialty fibres with high non-linear coefficient (γ) with high CW signals providing a real (single pump) or virtual (dual pump) mirror plane. These considerations lead directly to two main challenges in OPC implementation – placement of the OPC at the mid-span of the link; and fibre effects due to high power intensities.

OPC utilises the transmission link itself to compensate for fibre impairments and thus depends on link symmetry. One of the original challenges of OPC installation was identifying and accessing the mid-span of the link in order to achieve optimum OPC benefit. In systems with high power variation across a span (e.g. EDFA systems), even in a purely symmetrical system, the regions of high non-linearity will occur at different accumulated dispersions which will reduce the amount of non-linearity that an OPC can compensate. It was proposed in [20] that the use of a tailored amount of dispersion compensating fibre at the OPC location could be used to compensate for this. Subsequent studies of this proposal [21] show that the use of simplified DBP combined with OPC results in up to an 80% reduction in DBP complexity compared to DBP alone provided the OPC may be placed with 6 spans of the midpoint of the link. Another approach is to ensure that the transmission power evolves symmetrically along the span, for example using ultra-long Raman fibre laser based amplification with second order pumping [22].

Brillouin scattering [23] is an effect where an interaction between acoustic phonons (molecular vibrations) and photons occurs. At high light intensities the generated phonons may result in stimulated light scattering counter to the signal propagation and result in a drastic reduction in the forward propagating pump power, limiting the wanted nonlinear effect. SBS suppression techniques depend on two basic principles – broadening the pump spectrum relative to the SBS bandwidth (1-10 GHz) [24] by dither or altering the physical properties of the fibre itself (e.g. core doping [26] or inducing strain/thermal gradients [27]) to dampen SBS accumulation.

Dithering techniques are widely used for SBS suppression with the level of broadening proportional to the increase in Brillouin threshold [24]. As these dither tones are typically in the MHz frequency range, they not only add to the complexity of the non-linear device, but they also impose a periodic phase shift on the converted signal. This may either be tracked in the digital coherent receiver [25] or, in the case of a dual pump or multi-section OPC, counter dithering may be employed to reduce the net phase modulation of the conjugate. SBS accumulation in the fibre itself may be tackled using multiple dissimilar fibre sections [28], core doping to alter the Brillouin coefficient, or by the application of varying strain from 100 g to 1000 g along the length of the fibre [29]. Recently a dispersion tailored strained HNLF has been developed which minimises the detrimental impact of SBS suppression on the OPC bandwidth [30].

3. PHASE SENSITIVE AMPLIFIERS CHALLENGES

Record levels in transmission distance have been achieved in all-optical regenerative systems using binary intensity modulated signals [31]. However, in today's systems information is not carried only in the amplitude but also in the phase of the optical signal. Competitive all-optical regenerators should be able to remove noise from both quadratures of m-QAM formatted signals. Similarly, as seem above (Figure 1b) simultaneous operation on wavelengths is of particular importance, allocated in a contiguous band for super-channel applications, i.e. optical OFDM. Amplitude noise suppression has been achieved using a variety of methods including filtered self-phase modulation [32], non-linear interferometers such as the non-linear loop Mirror (NOLM) [33] and the Mach-Zehnder [34]. Such schemes have also been adapted for multi-wavelength [35] operation. Amplitude noise suppression of phase encoded signals has been achieved through phase preserving amplitude effects [36], and phase-to-amplitude conversion with subsequent amplitude noise suppression [37]. However, the most effective approach is to use the phase squeezing properties of a phase sensitive amplifier (PSA) [38]. The successful extraction of a local phase reference from an incoming signal [39] enabled the demonstration of the first “black-box” PSA regenerator for binary phase encoded signals (BPSK) [40]. Furthermore a PSA may be used as an optical phase quantiser for an arbitrary number of levels [41].

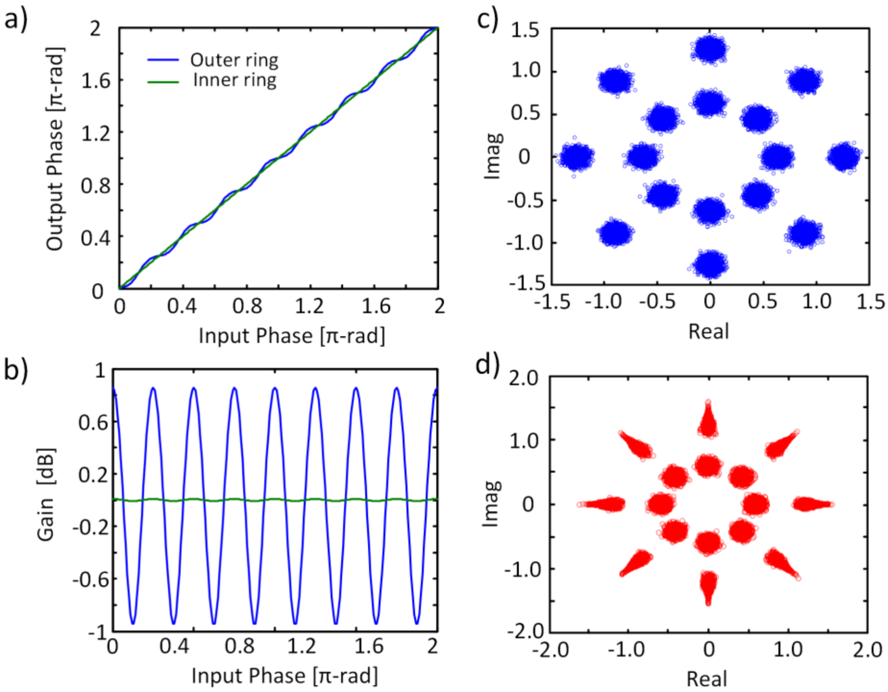

Figure 2 a) Phase and b) gain responses of an 8-level PSA that correspond to the two amplitude levels of a 2-ASK/8-PSK signal. The responses have been jointly optimised to maximise the symbol error rate performance of a single stage regenerative link. c) Constellation diagram of the 2-ASK/8-PSK signal degraded by ASE noise at the input of the PSA. d) resulting constellation at the PSA output.

Despite excellent progress, multi-wavelength m-QAM regenerators still face several key challenges, including phase recovery, transfer function optimisation, power consumption and expansion of the channel count. For example local carrier synchronisation has been demonstrated only for BPSK and QPSK signals [43], and the difficulties beyond this are well known in the DSP community. For dense constellations, PSA noise squeezing should be equally effective for all constellation points. Whilst recently proposed PSA transfer functions allow such uniform regeneration [42], the simplest PSA configurations involving the direct combination of multiple signal harmonics in a second PSA do not, since they contain a high order dependence on the amplitude waveform of the input signal. Fig.2 (a-d) illustrates this effect on the phase and gain response for an eight-level PSA based phase quantiser [43], designed to operate with 2-ASK/8-PSK signals.

Clearly more complicated designs, where selected harmonics are stripped of their higher order amplitude modulation (e.g. using a phase preserving amplitude limiter) and acquire that of the original signal before entering the PSA, will restore the required uniform staircase phase response for multiple amplitude levels [42]. Simultaneous suppression of the amplitude and phase noise may also be achieved by combining PSA's and nonlinear interferometers configurations [44]-[47]. The practical realisation of such designs with uniform regeneration presents a number of technical challenges. Interferomteric multi-level quantisers require non-linear phase shifts of multiple π-rads. Currently, only highly non-linear fibres of relatively long length (>500m) can meet this requirement at moderate input optical powers (< 5 W). Such fibre based interferometers are extremely vulnerable to environmentally induced acoustic noise effects detrimentally impacting the outage probability of a cascaded regenerative system. Non-incremental improvements in the field of integrated highly non-linear devices (e.g. Si based nanowires or Photonic Crystals) [48]-[49] or the gain dynamics of active nonlinear materials [51] are therefore necessitated, for the development of such innovative regeneration concepts [44]-[47],[50].

The first (2 channel) multi-wavelength regenerators for phase encoded signals were enabled using PSA schemes [51]. Extension of these schemes to higher order formats and a greater number of channels are required in order to enable practical application in telecommunication networks. The schemes proposed to date rely on the multiplicative nature of the parametric mixing process which creates many required (and unwanted) inter-mixing products that may interfere with the input signals. A wise placement of the incoming signals and the local pumps in the frequency spectrum is therefore necessitated and results in a significant increase in the occupied spectrum. Thus in addition to reduced size and energy consumption, future nonlinear devices should offer significantly enhanced bandwidths [52] to accommodate the rich spectrum associated with multi-channel regeneration.

CONCLUSIONS

Non-linear optical devices offer the prospect of increasing the total data throughput of a single optical fibre, and their advantage in this regard is sufficient to overcome the energy penalty associate with their implementation. Many challenges in developing non-linear optical devices have been solved recently and those that remain – energy consumption optimisation; high optical power handling; multi-wavelength operation of multi-level amplitude and phase regenerators – are now well understood. The seeds of practically devices are under development which will result in realisable devices which will allow transmission beyond the currently accepted nonlinear-Shannon limit.

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