The Role of Distributed Raman Amplification in the Times of the "Capacity Crunch"

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ABSTRACT
Distributed Raman amplification has different roles to play in combination with of a range of potential solutions to deal with the nonlinear Shannon limit. Here, we will cover issues such as asymmetry optimisation for optical-phase conjugation nonlinear compensation, the combination of optimised distributed amplification with digital nonlinear compensation techniques and the challenges of adopting high-spectral density formats while still making use of all the possible available bandwidth. Some examples are drawn from recent results from the past few years.

Keywords: Distributed Raman amplification, ultralong lasers, optical phase conjugation, capacity limits.

1. INTRODUCTION

Distributed Raman amplification has paved the way in recent years for efficient management of signal power along transmission over a broad bandwidth, bringing with it improved noise performance and additional bandwidth that can be exploited for capacity. Simultaneously, over the course of the past decade, single-mode optical fibre capacity has caught up with the once seemingly remote limit defined by Shannon's information theory corrected for nonlinearity [1,2]. Finding a way to circumvent this conundrum, guaranteeing the role of telecommunications as a motor for technological and societal development in the future, is a challenge as important as any other the scientific community will face over the next few years. Several techniques have been proposed to compensate or partially mitigate fibre nonlinear effects, from pre-shaping and in-line nonlinearity management [3-5] to digital compensation through back-propagation [6-8] and physical mitigation through optical phase conjugation (OPC) [9,10]. In this paper, we will endeavor to explain the important role that distributed Raman amplification is currently playing and is bound to play in the future as part of such solutions or in combination with them.

2. DRA AND NONLINEARITY MANAGEMENT

The most important advantage provided by distributed Raman amplification is, of course, its improved noise performance when compared to traditional lumped amplification. This improved noise performance comes from the actual distribution of gain along the transmission link, and comes with the additional perk of allowing a limited control over nonlinearity [11], i.e., over the local intensity of the signal along the fiber span. This means that it should be possible to optimally design the amplification scheme to minimise nonlinear impairments under the constraints of a particular transmission system and format. Recent experimental work using higher order, distributed bi-directional amplification in combination with digital back-propagation for nonlinearity mitigation with high-density formats [12] shows great promise for long-haul and unrepeatered transmission. In addition to its improved optical noise performance, distributed Raman amplification is particularly interesting thanks to its capability to provide broadband amplification [13] through the use of multiple pumps, allowing for extended bandwidth and capacity. Moreover, as was shown in [14], relatively simple second-order amplification schemes, such as those based on ultra-long Raman fibre lasers (URFLs), can provide extended bandwidth amplification even from a single frequency pump.

In order to find the optimal amplifier configuration in any such system, we have recently developed a general, simplified, approach based on the multi-level optimization procedure first presented in [4, 11], now adapted to account for modern transmission formats and additional degrees of freedom, such as partial loss compensation. The method works with any form of WDM configuration, reducing simulation time by searching for optimal sets of parameters in in the system configuration space that satisfy the conditional minimization of optical signal-to-noise ratio (OSNR) for any given value of the accumulated nonlinear phase shift (NPS). Different transmission formats present a different ideal balance between noise and nonlinearities, but the optimal performance will correspond in any case to a given point in the defined optimal trajectory. Moreover, the defined optimal trajectories in the parameter space are fully compatible with the solutions obtained by solving the same problem through NLSE simulations. In the examples shown below, the amplification scheme of choice is a typical cavity URFL pumped at 1366 nm, with high reflectivity (95%) gratings at 1455 nm, which can be described through a set of boundary-value coupled ordinary differential equations for the pumps and carrier channels. From the numerical solution of these equations it is possible to extract the NPS and OSNR for any of the particular subchannels, in order to define the corresponding optimal trajectories.

From a system design standpoint, the immediate consequence of the improved spectral efficiency offered by modern transmission formats is an increase in signal power spectral density and pump depletion, which affects the amplifier power budget and modifies the optimal trajectories in the configuration space. This is particularly important for unrepeatered transmission, as seen in Figs 1 and 2, below, showing the optimal trajectories for an URFL 250 km amplifier pumped at 1366 nm, projected in the channel power vs. pump ratio plane for a given percentage of loss compensation. The red isolines denote fixed values of the nonlinear phase shift, whereas the black ones represent lines of identical OSNR. Fig 1(left) shows the optimal trajectories for the close-to ideal situation of transmission of a single DP-QPSK channel, in which optimal pump power split is always close to 50%. Fig 1(right) illustrates the impact of adding just 4 more DP-QPSK channels with a 50 GHz spacing, which immediately modifies the optimal pump power split for channel powers above -10 dBm, requiring a larger proportion of forward pump power to improve OSNR. For 8 and 16 channels (not in the figure), the optimal forward pump ratio is drown towards 60% for high input signal channel powers. Still, performance for a 50% split can be expected to be not far from optimal, and a compromise can be found in amplifier system design in terms of easy scalability.

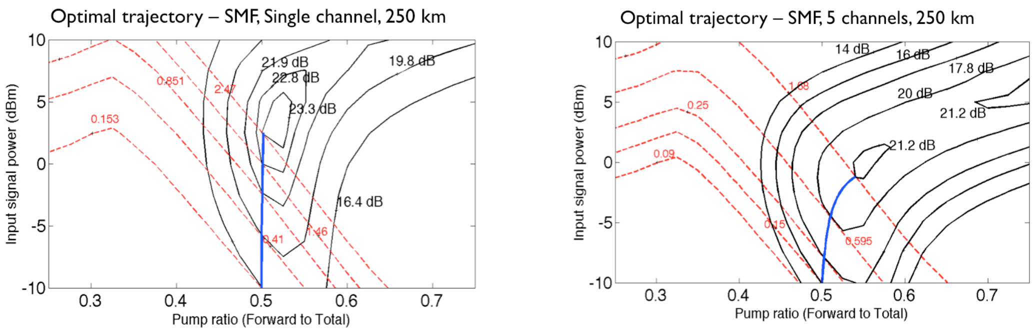

Fig 1. Optimal trajectories in the amplification scheme configuration space for URFL amplification in (left) single-channel DP-QPSK, (right) 5-channel DP-QPSK, 50 GHz spacing,

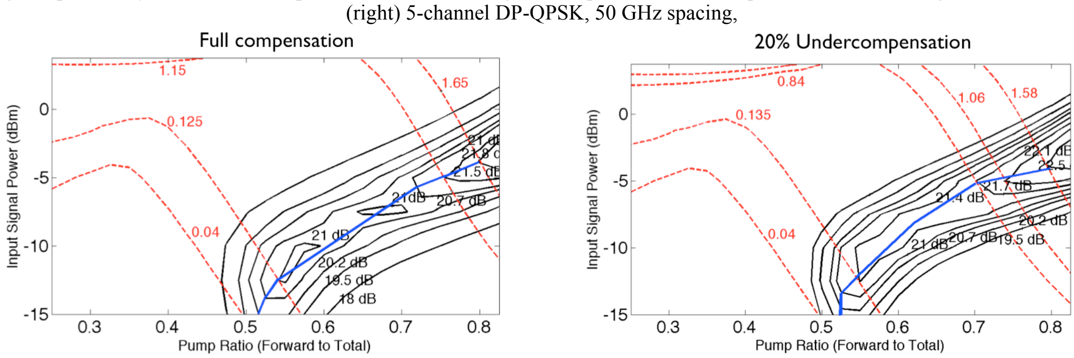

Fig 2 . Optimal trajectories in the amplification scheme configuration space for URFL amplification in (left) 70-carrier Nyquist-PDM-16QAM, (right) 70-carrier Nyquist-PDM-16QAM with 20% undercompensation

In comparison, Fig 2(left) displays the optimal trajectories for a 70-carrier Nyquist-PDM-16QAM over a 700 GHz spectral bandwidth. With optimal power per sub-channel close to -5 dBm (see, for example [4]), optimal pump split would shift towards 80% forward. This would be entirely unpractical due to the higher amounts of RIN transfer to be expected from forward pumping at such gain levels, and would require forward pump powers in excess of 9 W, far from reliable for continuous operation. Nevertheless, attenuation compensation is rarely convenient in unrepeatered transmission, so Fig 2(right) displays the optimal trajectories for the same 70 – carrier Nyquist system of Fig 2(left) with a 20% power penalty, trajectories which are barely modified. Note that this situation arises even for a total bandwidth of just 700 GHz, for which single-wavelength Raman 2^{nd}-order Raman amplification scheme can suffice. This suggests that purely distributed multi-wavelength Raman pumped amplification solutions for unrepeatered superchannel transmission encompassing the C or the C+L windows might prove to be unable to deal with scalability, and would be incapable of reliable operation due to the high pump power requirements.

Switching to long-haul transmission, the picture is rather more optimistic. Here, span length becomes one more parameter in the configuration space, which provides some more room for minimising the impact of the increased spectral density. As an example, Fig 1(left) displays the optimal trajectory for an 80 km SSMF span. Here optimal operation is achieved for a pump split close to 50%, in which power excursion (Fig 2(right)) is minimized and the best balance between noise and nonlinearities achieved, as corresponds to a quasi-lossless transmission regime.

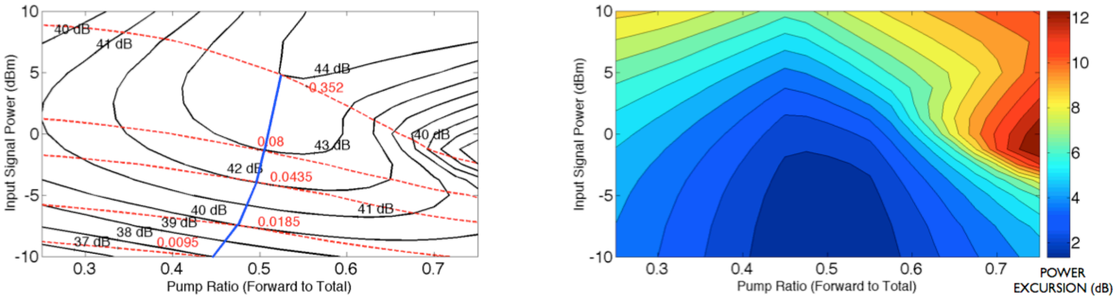

Fig 3. (left) Optimal trajectories in the amplification scheme configuration space for a URFL-amplified 70-carrier Nyquist-PDM-16QAM transmission system with an 80 km ITU G.652 fiber span. (right) Signal power excursion in the same parameter space.

3. DRA AND OPTICAL PHASE CONJUGATION

Nonlinear mitigation through OPC has been recently used, in combination with URFL-based Raman amplification, to successfully demonstrate, for the first time, long-haul transmission at capacities above the nonlinear Shannon limit [15]. This achievement has the potential to be built upon through optimal design of the distributed amplification system. The degree of nonlinear compensation using mid-link OPC is related to the asymmetry match of the conjugated and transmitted signal power evolution in the fibre. The key to maximise performance in OPC-assisted systems lies in reducing signal power asymmetry within the periodic spans while ensuring a low impact of noise and non-deterministic nonlinear impairments in the overall transmission link. Recently, we demonstrated theoretically that almost ideally symmetrical signal power evolution can be achieved in advanced distributed amplification schemes, with the best results obtained for half- open-cavity random distributed feedback (DFB) Raman laser amplifier with bidirectional 2nd order pumping [16]. This setup allows to potentially reduce signal power evolution asymmetry inside the span with respect to its middle point to a mere 3% over a realistic span length of 62 km SMF, which constitutes the lowest asymmetry level achieved up to date on such a long span [17]

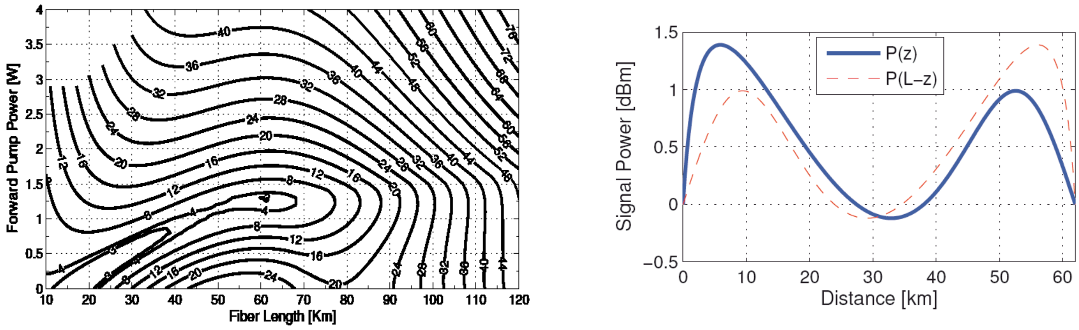

Fig 4. (right) Signal power asymmetry with respect to the centre of the span for a 62 km link amplified with a random distributed feedback 2nd – order ultralong Raman fibre laser, vs. forward pump power, for a single-channel signal launch power of 0 dBm. (left) Signal power evolution profiles for the lowest asymmetry case.

In order to achieve this, the optimal ratio between forward and backward pumping has to be found, as exemplified in Fig.4 (left), that represents the percentual signal power asymmetry with respect to the centre of the span, defined as

$$Asymmetry = \frac{\int_0^{L/2} |P(z) - P(L-z)| dz}{\int_0^{L/2} P(z) dz} \times 100$$

for different values of forward pump power, with backward pump power adjusted for full attenuation compensation. Figure 4 (right) shows the signal power evolution profiles for the configuration with minimal power asymmetry. The lower the asymmetry, of course, the lower the residual nonlinearity after mitigation via OPC. Similar results have been recently obtained in multichannel transmission with broadband amplification, with very similar asymmetry levels achieved for 20 simultaneous channels.

4. DRA IN OTHER CONTEXTS

In addition to its direct advantages in nonlinear mitigation through OPC, DRA has been successfully demonstrated in combination with several other nonlinear mitigation techniques in recent times, including digital back-propagation [12], and recently nonlinear inverse synthesis [18], even without quasi-lossless transmission. Several of these results will be reviewed in our presentation.

5. CONCLUSION

Distributed Raman amplification is one of the key technologies that will allow the community to face the "capacity crunch" challenge. Not only does DRA offer the possibility of exploiting an extended transmission bandwidth, but can significantly contribute to the efficiency of nonlinearity mitigation, both through physical and digital processing. We have reviewed some of the novel approaches designed to optimise signal transmission to improve nonlinear mitigation.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support of the EU through the FP7 ITN programme ICONE (608099), the Marie Sklodowska-Curie individual fellowship 'CHAOS' (658982), as well as Spanish grants ANOMALOS (TEC2015-71127-C2) and SINFOTON (S2013/MIT-2790-SINFOTON-CM).

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