Comparing Networking Benefits of Digital Back-Propagation vs. Lightpath Regeneration

Comparing Networking Benefits of Digital Back-Propagation vs. Lightpath Regeneration

Mattia Cantono, Roberto Gaudino, Pierluigi Poggiolini, Vittorio Curri

DET, Politecnico di Torino, Italy, www.optcom.polito.it, mattia.cantono@polito.it

Abstract *We compare the networking benefits of Ideal Single-Channel Digital-Back-Propagation (ISC-DBP) vs. Lightpath Regeneration as Quality-of-Transmission enhancing techniques. By analyzing three different topologies, we show that ISC-DBP has the potential to substantially reduce the number of required regenerators in all-optical networks.*

Introduction

Nonlinear Interference (NLI) induced by the Kerr effect in fiber propagation is the most significant impairment in optical fiber communication systems and networks[1,2] operated by DSP-based transceivers exploiting multilevel modulation formats. In recent years, substantial effort has been aimed at developing Non Linear Compensation (NLC) methods. One of the most investigated techniques is Digital Back Propagation (DBP). It mitigates NLI by solving the inverse nonlinear Schrödinger equation backward through the fiber link[3-4]. In this work, following recent assessments of DBP limits on point-to-point fiber systems[5-7], we analyze its benefits in a reconfigurable optical network scenario. Our investigation is driven by the need of assessing networking merits of transmission technologies. This is a key requirement for the evaluation of the enabling technologies needed to sustain the expected growth of IP traffic[8], while maximizing network operators' return over investments on the already installed fibers and optical amplifiers[9]. Therefore, operators are looking for solutions able to maximize networking benefits only upgrading the nodes' equipment.

By making use of a modified version of the recently proposed Statistical Network Assessment Process (SNAP)[2,10], we evaluate the benefits of Ideal Single-Channel (ISC) DBP on three uniform and uncompensated backbone networks: a German, a Pan-EU and a US topology[11]. We discuss how ISC-DBP can reduce the number of optical-electro-optical (OEO) regenerators needed to allocate an any-to-any connectivity, enabling operation also on low Quality of Transmission (QoT) lightpaths. We consider the use of *rigid* transceivers able to operate a unique modulation format at a given rate. We take into account both PM-QPSK (100 Gbps) and PM-16QAM (200 Gbps) transceivers.

Methodology

We consider a reconfigurable WDM optical network with any-to-any connectivity already implemented through the assignment of lightpaths (LPs) allocated over links operating at full spectral load. Over each link, the power per LP is supposed to be constant for all WDM channels and optimized according to the Locally–Optimized–Globally–Optimized (LOGO) principle[12,13]. We consider the LPs to have been allocated using a Quality of Transmission (QoT) based routing policy with first fit wavelength assignment[2,10]. We assume network nodes equipped with *rigid* transceivers, hence, to establish node-to-node transparent connections, the QoT of each LP must be larger than a given threshold, established by the modulation format and by FEC coding.

The metric defining the QoT of LPs is the generalized Optical Signal-to-Noise Ratio (OSNR) including both ASE noise and NLI. The latter can be computed through the Incoherent Gaussian Noise (IGN) model[5]. For each LP implementing the any-to-any connectivity, we verify that the related OSNR is larger than the threshold.

For LPs below threshold – the underperforming LPs (ULPs) – we consider the application of three QoT enhancing techniques: (i) lightpath regeneration (LR) via OEOs, (ii) ISC-DBP at the receiver, (iii) a mix of (i) and (ii). If none of these strategies is effective, the LP is considered to be out of service (OOS). In general, the use of ISC-DBP is more favorable than LR since the former does not affect the transparency of the network. We do not consider multichannel DBP because side channels can be added and dropped at any node thus making it ineffective.

We compare ISC-DBP to LR by counting how many ULPs can be enabled by using solely ISC-DBP. For ULPs for which ISC-DBP is not effective on its own, we evaluate its joint application with LR to reduce the number of required OEOs enabling the minimum OSNR requirement. We present the ISC-DBP advantage over LR as percentage of saved OEOs with respect to a full LR scenario.

Fig. 1: The considered network topologies[11]. **Left)** German. Average link length 207 km **Middle)** Pan-EU. Average link length 637 km **Right)** US. Average link length 1463 km.

In order to compare the considered strategies, we need to evaluate the related OSNR improvement. In case of LR such process is straightforward once OEOs' locations have been identified. For OEOs placement we apply a greedy strategy based on the "minimum stops"[14] algorithm. To evaluate the benefit of ISC-DBP we compute the NLI generated by a single channel onto itself – the so called self-channel interference (SCI) – and subtract it from the total NLI power. So, the LP OSNR after ISC-DBP is:

$$OSNR_{DBP} = \frac{P_{TX}}{P_{ASE}+P_{NLI}-P_{SCI}}, \quad (1)$$

where P_{TX} is the LOGO-defined power per LP, and P_{ASE} and P_{NLI} are the power of ASE noise and NLI in the LP bandwidth B_{ch}, respectively. P_{SCI} is the SCI power removed by the ISC-DBP. To compute P_{SCI} we use of the Enhanced GN (EGN) model[15]. The ISC-DBP may enable a power per LP larger than the LOGO one, thus further improving the LP OSNR. However, we have verified that in the analyzed scenarios, such OSNR increase is negligible, being smaller than 0.08 dB. So, we did not include such a refined analysis, and use the LOGO approach.

System Results

We perform the described analysis on three network scenarios (see Fig.1). We consider a German topology made up of 17 nodes and 26 links, a Pan-EU network made of 28 nodes and 41 links, and a US network made of 14 nodes and 21 links[11]. Links are supposed to be bidirectional, uniform and uncompensated fiber-pairs. For the three networks all links are considered to consist of Single Mode Fiber (SMF) with 0.2 dB/km attenuation, 16.7 ps/nm/km dispersion and 1.3 1/W/km non-linear coefficient, and to be operated on the 50 GHz grid, exploiting the full 4 THz C-band. We assume lumped EDFA amplification, with 5 dB noise figure and suppose 18 dB as excess node loss, recovered by an additional amplifier.

We first consider *rigid* transceivers using PM-QPSK, then we consider a second scenario with devices based solely on PM-16QAM. For both, we suppose a gross symbol rate R_{sG}=32 GBaud, including a 28% FEC+protocol overhead, and a corresponding pre-FEC BER level of $4\cdot10^{-3}$. Hence, LPs may carry 100 Gbps or 200 Gbps

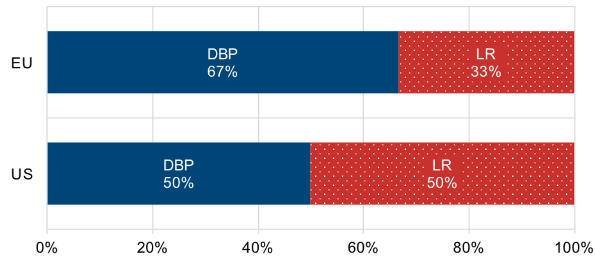

Fig. 2: Percentage of ULPs enabled by DBP and LR in the PM-QPSK transceivers' scenario.

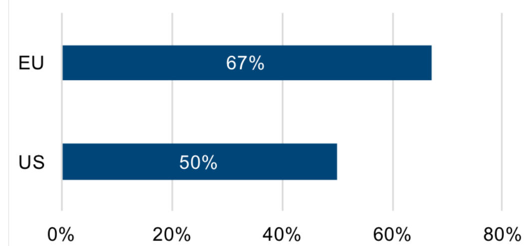

Fig. 3: OEOs saving [%] for PM-QPSK transceivers' scenario. For the German topology there are no ULPs.

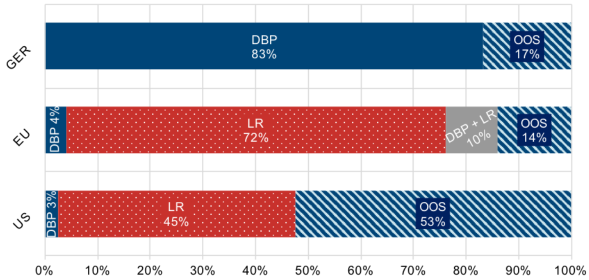

Fig. 4: Percentage of ULPs enabled by DBP, LR, BDP+LR or out of service (OOS) in the PM-16QAM transceivers scenario.

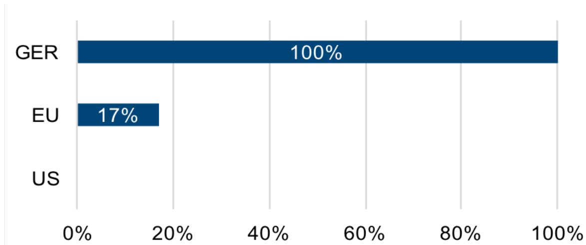

Fig. 5: OEOs saving [%] for PM-16QAM transceivers scenario.

when transceivers are operated using PM-QPSK or PM-16QAM, respectively. The minimum required OSNR calculated in B_{ch}=R_{sG} is 8.47 dB and 15.13 dB for PM-QPSK and PM-16QAM, respectively.

In Fig. 2 we show, for the PM-QPSK scenario, the percentage of ULPs that are enabled by each of the three considered strategies – LR, ISC-DBP, and a mix of the two – and the percentage of OOS ULPs, for the Pan-EU and US topologies. For the German network, OSNR for all LPs is above threshold, enabling to transparently carry PM-QPSK without the need for any QoT-enhancing technology. Note that for the other two topologies, all ULPs can be successfully routed by solely upgrading nodes' equipment either via LR or ISC-DBP, without the need for a mix of the two. For the Pan-EU network, ISC-DBP can be used to successfully transmit 67% of ULPs. For the remaining 33% of ULPs, LR must be used. For the US scenario, the percentage of ULPs enabled by the ISC-DBP decreases to 50%. This is due to the longer average link length of this topology: many LPs undergo large QoT degradation, that cannot be recovered by DBP.

Fig.3, for the use of PM-QPSK transceivers, shows the percentage of OEOs that can be saved by adopting ISC-DBP: 67% and 50% for the Pan-EU and US scenarios, respectively. Notice that the two percentages equal the ones of Fig. 2, because in these scenarios there is no need of mixed OEO/ISC-DBP solutions, thus using ISC-DBP on one LP saves one OEO.

Fig. 4 and Fig. 5 refer to the scenario where only *rigid* PM-16QAM transceivers enabling 200 Gbps/LP are used. In this scenario, QoT enhancing is needed also in the German topology. Referring to Fig. 4, we can observe that ISC-DPB is effective in the regional-area German topology, as it enables 83% of ULPs. Such effectiveness dramatically drops to 4% and 3% for the larger-area Pan-EU and US topologies, respectively. For these topologies, LR is indeed the most effective solution enabling 72% and 45% of ULPs for the Pan-EU and US networks, respectively. The cause of such a behavior is due to the different nature of the two considered countermeasures to the poor QoT of LPs. LR decouples the OSNR degradation and is consequently always effective, provided that the node-to-node OSNR degradation keeps the QoT above threshold. In such cases, LR can work by simply adding OEOs in each node traversed by ULPs. On the other hand, ISC-DBP acts on the entire LP from the origin to the destination node, so it is effective only on LP characterized by a limited gap with respect to the required OSNR. In particular, such a gap cannot exceed the effectiveness in OSNR enhancement of ISC-DBP in the considered scenario. However, ISC-DBP can be used together with LR, in order to reduce the number of OEOs required for very long, multiple hops ULPs, as it happens for the Pan-EU topology, where 10% of the ULPs are enabled by the mixed technique. In Fig. 4 it can also be observed that for all the three topologies, the considered QoT enhancing techniques are not sufficient to adequately improve the OSNR of all ULPs. In the US network, ISC-DBP, LR and their joint use, enable less than 50% of the ULPs. The cause is the presence of several links introducing a large OSNR degradation that can only be counteracted improving link quality, hence upgrading in-field equipment, i.e., fibers and/or amplifiers. For instance, some Raman pumping can be added to the EDFAs, enabling Hybrid EDFA/Raman Fiber Amplifiers (HFA), and consequently reducing the noise figure.

In Fig. 5 we can observe that ISC-DBP allows to completely remove OEOs in the German topology, while in the Pan-EU one, the percentage of removed regenerators drops to 17%, and for the US topology, ISC-DBP cannot save any OEO.

Comments and Conclusions

We have addressed the comparison of ISC-DBP and LR as QoT enhancing techniques showing that ISC-DBP enables a substantial reduction of the number of regenerators in different networks with PM-QPSK (100 Gbps/LP) transceivers. A similar level of effectiveness can be achieved with PM-16QAM (200 Gbps/LP) transceivers only in smaller regional-area networks such as the German one. For larger-area networks, QoT enhancing techniques are not sufficient to achieve 200 Gbps/LP and in-field enhancing techniques such as HFA are needed.

Acknowledgements

The authors would like to thank Fernando Guiomar for the fruitful discussions on the topics of this paper.

References

[1] Essiambre R.J. et al., "Capacity Limits of Optical Fiber Networks," JLT, p.662, 2010
[2] M. Cantono *et al.,* "Data-rate figure of merit for physical layer in fixed-grid reconfigurable optical networks," OFC 2016, Tu3F.3.
[3] E. Ip et al., "Compensation of dispersion and nonlinear impairments using…," JLT, 26, pp. 3416-3425, 2008.
[4] Guiomar F. et al., "Mitigation of intra-channel nonlinearities using a frequency-domain Volterra series equalizer," Opt. Express, 20, p. 1360, 2012
[5] P. Poggiolini *et al.,* "The GN-Model of Fiber Non-Linear Propagation and its Applications," *JLT*, 32, p694, 2014.
[6] T. Tanimura, et. al., "Analytical results on back propagation nonlinear compensator with coherent detection," Opt. Express 20, 28779-28785 (2012)
[7] R. Dar et. al., "On the Limits of Digital Back-Propagation in Fully Loaded WDM Systems". PTL, 28, no. 11, pp. 1253-1256
[8] Cisco, "Cisco visual networking index: Forecast and methodology, 2014- 2019," Tech. Rep., May 2015.
[9] G. Wellbrock, "How Will Optical Transport Deal With Future Network Traffic Growth?", ECOC 2014, Th.1.2.1
[10] M. Cantono et al., "Potentialities and Criticalities of Flexible-Rate Transponders in DWDM networks: a Statistical Approach," to appear on JOCN
[11] Betker A. et. al., "Reference Transport Network Scenarios", MultiTeraNet Report, (2003).
[12] P. Poggiolini *et al.,* "The LOGON strategy for low-complexity control plane implementation in new-generation flexible networks," *OFC 2013, OW1H.3*
[13] R. Pastorelli et al., "Network Planning Strategies for Next-Generation…," JOCN, 7, p. A511, 2015.
[14] G. Brassard et al., "Fundamentals of Algorithmics" Prentice Hall (1998)
[15] A. Carena et. al., "EGN model of non-linear fiber propagation", Opt. Express, 22, p. 16335, (2014)