Demonstration of EDFA Cognitive Gain Control via GMPLS for Mixed Modulation Formats in Heterogeneous Optical Networks

Juliano Oliveira[(1)], Antonio Caballero[(2)], Eduardo Magalhães[(1)], Uiara Moura[(1)], Robert Borkowski[(2)], Giovanni Curiel[(1)], Alberto Hirata[(1)], Luis Hecker[(1)], Edson Porto[(1)], Darko Zibar[(2)], José Maranhão[(3)], Idelfonso Tafur Monroy[(2)], Julio Oliveira[(1)]

[(1)] CPqD Foundation, Rod. Campinas/Mogi Mirim, km 118.5, Campinas, SP, Brazil, jrfo@cpqd.com.br
[(2)] DTU Fotonik, Tech. Univ. of Denmark, DK-2800 Kgs. Lyngby, Denmark, acaj@fotonik.dtu.dk
[(3)] PADTEC, Rod. Campinas/Mogi Mirim, km 118.5, Campinas, SP, Brazil, jmaranhao@padtec.com.br

Abstract: *We demonstrate cognitive gain control for EDFA operation in real-time GMPLS controlled heterogeneous optical testbed with 10G/100G/200G/400G lightpaths. Cognitive control maintains the network BER below FEC-limit for up to 6 dB of induced attenuation penalty.*
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1. Introduction

Next generation optical networks will be of a highly heterogeneous nature, ranging from elastic bandwidth, mixed modulation formats and flexible grid for spectrum allocation [1–5]. One implication of this new paradigm is that optical elements, like the omnipresent erbium-doped fiber amplifiers (EDFAs), need to dynamically support lightpaths with different characteristics. Control algorithms to stabilize EDFAs channel power control in networks with ROADM have been reported [6]. Solely, it does not provide dynamic control of gain flatness (GF) and noise figure (NF), relevant for links supporting advanced modulation formats, such as dual-polarization (DP) quadrature phase-shift keying (QPSK) or 16-ary quadrature amplitude modulation (16-QAM) in dense wavelength division multiplexed (DWDM) networks.

We propose the use of a novel cognitive approach, in particular the capability of learning from previous knowledge [4, 5], for EDFA gain control to ensure stable quality of transmission (QoT) for heterogeneous optical lightpaths. In this paper, we present the first experimental demonstration of real-time cognitive EDFA gain control in a GMPLS controlled autonomous testbed. The testbed is based on a replication of Brazilian GIGA network branch, with 10/100/200/400G lightpaths including mixed-modulation formats: DP-QPSK, 16-QAM and coherent optical (CO) orthogonal frequency division multiplexing (OFDM) DP-QPSK superchannel. The cognitive control includes the EDFAs fitness power mask used in the testbed to ensure bit error rate (BER) below 7% of forward error correction (FEC) threshold for all network lightpaths under attenuation penalty of up to 6 dB.

2. Cognitive EDFA control concept

The use of cognition for optimizing EDFAs operation point is based on the knowledge of a fitness power mask for each EDFA in the network. In our reported experiment, all EDFAs were characterized with respect to GF and NF. We considered 40 non-modulated WDM channels in a 100 GHz grid (entire C-band) as the input signal to each EDFA. The characterization procedure consisted of measuring the GF and NF values for each combination of gain and total input power, see Fig. 1. For the purpose of illustration, Fig 1(a) and (b) shows an example of such characterization. For each total input power and gain value combination, a plot of NF×GF was built for each EDFA, as exemplified in Fig. 1(c) for the case of input power of -15 dBm. A target vector optimization method [7] was implemented to simultaneously optimize NF and GF, acting on the objective space as illustrated in Fig. 1(c).

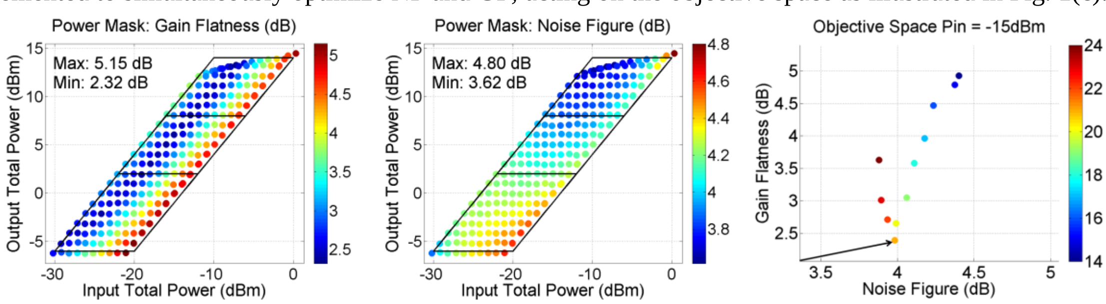

Fig. 1: Optical amplifier operational point adjustment: (a) Gain flatness, (b) Noise figure, (c) Example of objective space optimization for input power of -15 dBm.

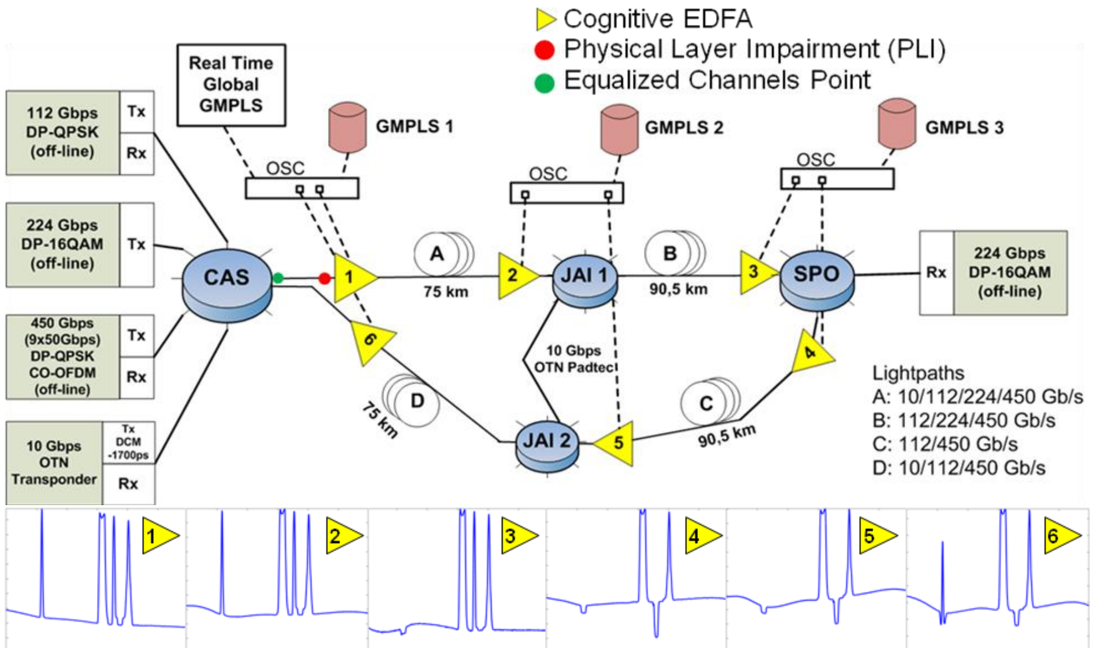

Fig. 2: Experimental setup of the implemented heterogeneous optical network. OSC: Optical supervisory channel.

A setpoint gain value is associated with each point in the objective space for the measured input power. The lowest Euclidian distance from the point to origin denotes the gain setpoint that gives better fitness result (lowest GF and NF). An example in Fig. 1(c) shows that the optimized setpoint gain is 21 dB for -15 dBm input power. In our testbed, the GMPLS control plane was adapted for EDFAs monitoring and configuration, implementing the corresponding collection, and communication via control channels. In this way, we were able to run live the above cognitive EDFA control algorithm, performing real time setpoint gain adjust in less than 1 second for all EDFAs in the testbed. As high values of optical power may induce undesirable non-linear fiber transmission impairments, two regimes are considered. LP1 regime makes strict restriction on allowed maximum launch power (LP) to minimize potential non-linear effects, but does not highly optimizes GF and NF. LP2 makes the trade-off between the minimization of NF and GF values for tolerance to non-linear effects. The allowed LP for LP1 is -2 dBm and for LP2 is 2 dBm. These values are accounted in the optimization algorithm restricting the adjusted gains to limit output powers below LP1 and LP2 levels.

3. Experimental implementation

Fig. 2 shows the experimental testbed, based on a replication of Brazilian GIGA experimental network branch Campinas (CAS), Jundiai (JAI), São Paulo (SPO), with implemented GMPLS real time control. Four different wavelengths were used, carrying different modulation formats: 10 Gb/s on-off keying (OOK) with chromatic dispersion (CD) pre-compensation (1535.82 nm), 112 Gb/s NRZ-DP-QPSK with offline coherent detection (1550.12 nm), 224 Gb/s pre-filtered 33% RZ-DP-16QAM with offline coherent detection (1547.72 nm), 450 Gb/s NRZ-CO-OFDM, (9×12.5 Gbaud DP-QPSK) with offline coherent detection (1545.32 nm). In Fig. 2 insets are shown each amplifier output power spectrum for the transmitted channels.

The testbed was composed of 3 nodes and 4 fiber spans, see Fig. 2. The first node (CAS) acted as a transmitter (Tx) for all 4 channels and receiver (Rx) for the 10 Gb/s, 112 Gb/s and 450 Gb/s. The 4 channels were transported to JAI1, where the 10 Gb/s channel was dropped. At SPO the 224 Gb/s 16-QAM channel was detected, whereas the 112 Gb/s QPSK and 450 Gb/s CO-OFDM were routed back to JAI2 where they were combined with the 10 Gb/s from JAI1 and transported all together to CAS. Induction of physical layer impairments (PLI) were generated by adding 3 or 6 dB attenuation at the input of the amplifier 1, the same point where channels were equalized, see Fig.2.

A distributed GMPLS control plane, comprising a standard GMPLS protocols stack with adaptations for DWDM layer is implemented. EDFAs were configured through the optical link management protocol (OLMP) using a centralized monitor. This monitor reads both EDFA dynamic (input power, output power and current calculated optical gain) and static parameters (device model) for all amplifiers along the GMPLS nodes, executes the cognitive EDFA control algorithm and configures all amplifiers in real time operation.

Tab. 1: Results of the cognitive EDFA with respect to launch power restriction method. OK/Fail =below/above FEC threshold.

PLI Att. (dB)	Channel Bit rate (Gb/s)	EDFA w/o cognition	Cognitive EDFA					
			No LP restriction		LP1 regime		LP2 regime	
		BER	G1-G6 After (dB)	BER	G1-G6 After (dB)	BER	G1-G6 After (dB)	BER
3	10	OK	21/23/24/ 21/23/21	OK	14/22/22/ 14/23/23	OK	16/23/20/ 14/23/21	OK
	112	OK		Fail		OK		OK
	224	Fail		OK		OK		OK
	450	Fail		Fail		OK		OK
6	10	Fail	20/23/20/ 23/23/21	OK	15/23/20/ 15/23/23	OK	18/23/21/ 14/23/21	OK
	112	Fail		OK		OK		OK
	224	Fail		OK		Fail		OK
	450	Fail		OK		OK		OK

4. Experimental results

Tab. 1 gathers the results for different attenuation PLI levels (3 and 6 dB) and launch power restriction methods performed in the testbed. OK/Fail indicates BER below/above the FEC threshold. Initially, considering the system without PLI, the gain of all the EDFAs were set to 17 dB, as it was enough to overcome all span losses with all channels operating below FEC limit. When a 3 dB PLI is induced in a system without EDFA cognition, only 10 Gb/s and 112 Gb/s channels are properly received. For 6 dB PLI, none of the channels are below the FEC threshold. When cognitive EDFA control is applied, without LP control, the performance is improved and only the 112 Gb/s and 450 Gb/s channels fail for 3 dB PLI due to nonlinearities caused by the high amplifier launch power levels. Next, when cognitive EDFA control with LP1 launch power constrain is implemented, the performance is improved even further and just the 224 Gb/s channel fails for 6 dB PLI due the low OSNR value. Finally, when cognitive EDFA LP2 control is employed, all channels are successfully detected for both 3 or 6 dB PLI. Fig. 3 shows an example of live time control of EDFAs with LP2 cognitive control, for the case of 6 dB induced PLI. We can clearly observe how at time 3s (Fig. 3) cognitive EDFA LP2 adjust the gain, to achieve BER performance below FEC-limit for 112/224/450 Gb/s channels, and beyond loss of signal (LOS) threshold for the 10 Gb/s channel.

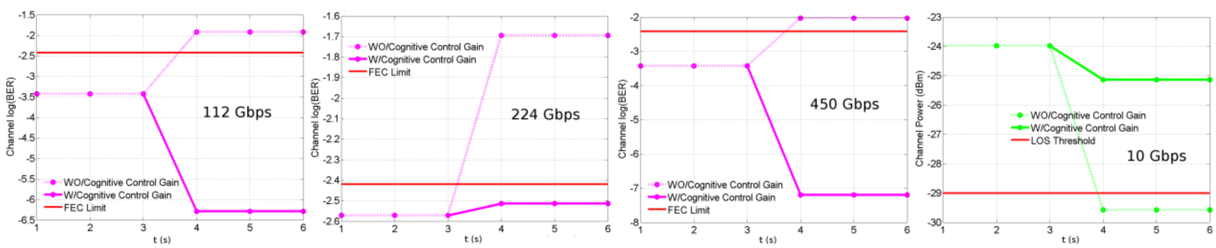

Fig. 3: BER measurements (purple) for 112/224/450 Gb/s channels and power (green) for 10 Gb/s channel after a 6dB attenuation event.

5. Conclusions

We experimentally demonstrated the benefits of cognitive EDFA gain control through a real-time GMPLS control plane for heterogeneous optical networks. The reported testbed includes 10/100/200/400G lightpaths with mix-modulation formats. Our result shows that under dynamic operation and induced attenuation events of up to 6 dB, the BER of lightpaths were maintained below 7% FEC threshold. The results show clearly the prospect of cognition to achieve self-perception and self-adaption to the current physical layer conditions which is of relevance in flexible and heterogeneous optical networks.

6. References

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