Cost-Effective Solution for High-Capacity Unrepeatered Transmission

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Abstract: A cost-effective 310-km SSMF unrepeatered optical link employing off-the-shelf EDFAs, 1st-order DRAs, and a ROPA is experimentally demonstrated. An iterative optimization process enabled a 12.8-Tbps net transmission (37.5-GHz spaced 128 channels $\times$ 100 Gbps).

OCIS codes: (060.4510) Optical Communications, (060.2360) Fiber optics links and subsystems.

1. Introduction

The exponential grown in the data volume transmitted globally has driven the need to an unceasing cycle of scientific breakthroughs pushing for new technological paradigms. At the same time, the market's increasing competition demands for economically viable solutions to reduce installation and maintenance costs of optical links, while improving their reach and transmission capacity [1] and diminishing their latency and energy consumption. Regarding unrepeatered optical systems [2], which can provide high-bandwidth and low-latency links to geographically isolated locations, recent published works show a clear tendency towards the adoption of solutions based on high-order distributed Raman amplification (DRA) jointly with remote optically pumped amplification (ROPA) in systems employing large-effective area and low-loss fibers [3–5]. Notably, cascaded pumping schemes in high-order DRAs allow a more homogeneous distribution of the channels propagation power, extending the link reach while avoiding system performance degradation due to fiber nonlinearities [6]. However, despite its improved performance, this kind of solution is still unfeasible for low-cost commercial implementation due to the need of expensive high-power pump lasers (typically higher than 5 W).

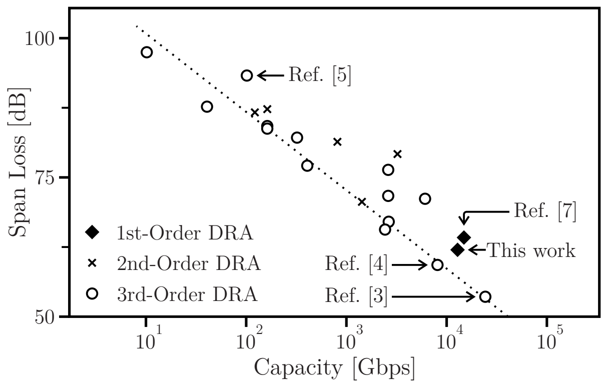

Fig. 1. Compilation of previous works.

Nevertheless, as shown in this work and evinced in Fig. 1, thanks to an iterative optimization process consisting of successive refinements of pre-emphasis launch power profile jointly with the remote amplifiers design, it is possible to achieve results near the state-of-the-art employing only 1st-order DRA (at both link ends), a ROPA at the receiver side, and standard single-mode fiber (SSMF). Therefore, the proposed method significantly reduces the link complexity and, consequently, provides a better compromise between performance and implementation cost. The employed process was designed to optimize (i) pumps allocation and power and (ii) Erbium doped fiber (EDF) length and distance from the receiver. This optimization aims to maximize the received optical signal-to-noise ratio (OSNR), equalized in the entire C-band, while flattening the maximum propagation power taking into account all channels and avoiding Kerr related nonlinear phenomena. Consequently, it was possible to achieve a capacity-reach product of 3.968 Pbps.km (128 channels $\times$ 100 Gbps over 310 km), employing commercial off-the-shelf transponders with conventional digital signal processing (DSP) algorithms. Moreover, compared with a similar high-capacity system based on 1st-order DRA and ROPA [7], the system here discussed achieved comparable capacity-reach product employing only cost-effective off-the-shelf boosters and pre-amplifiers (*i.e.*, without lumped Raman amplifiers and dispersion pre-compensation) in a 37.5-GHz flexgrid, occupying a narrower optical bandwidth due to the denser channel spacing. Therefore, the achieved high-capacity (12.8 Tbps) cost-effective (SSMF based with off-the-shelf amplifiers) unrepeatered link is a viable solution for commercial applications.

2. Experimental Setup

The experimental setup is presented in Fig. 2, encompassing an off-the-shelf 1st-order DRA (Padtec, 30-dBm total pumping) at the transmitter side. At the receiver side, a amplification unit was designed to simultaneously provide 1st-order distributed Raman amplification and pump the remote optical amplifier. Furthermore, off-the-shelf Erbium doped fiber amplifiers (EDFAs) were employed as booster and pre-amplifier. At the transmitter side, 128 channels, fully occupying the extended C-band (from 1528.9 nm up to 1566.7 nm), were emulated through a filtered amplified spontaneous emission (ASE) noise profile [8], designed to correspond to the equalized received OSNR for all channels, as shown in Fig. 3(a). The spectrum of 64 channels in a 75-GHz grid were employed as reference to equalize the ASE profile emulating the 128 channels transmission (as shown in the same figure). As highlighted in this figure, the 128-channels spectrum is 3 dB attenuated when compared to 64 channels, as expected due to the number of channels doubling. In order to evaluate the received BER in real time, the ASE profile is attenuated in the region of the channel under test and its adjacent channels, according to the 37.5-GHz ITU-T grid. Then, three off-the-shelf transponders (Padtec) modulated at a 100-Gbps DP-QPSK data rate (line rate equal to 128 Gbps encompassing a 28 % overhead) are allocated and equalized ensuring that the total power of each channel corresponds to the equalized ASE profile, as also highlighted in Fig. 3(a).

Following, the channels set is amplified by a booster and coupled to the transmission Raman pumps, composed by four 300-mW lasers, and launched in a 210-km SSMF span. The 1st-order Raman gain peak occurs after about 30 km of propagation, designed to allow the maximum propagation power avoiding nonlinear transmission impairments while flattening the profile in the entire transmission band. This is specially critical at shorter wavelengths, where the Raman gain peak and the pre-emphasis profile, designed to ensure OSNR equalized reception, induce higher maximum propagation power. Subsequently, the optical signal, with its power reduced by the 0.2-dB/km SSMF mean attenuation, reaches the ROPA composed by about 11 m of a commercial off-the-shelf EDF pumped by four 500-mW counter-propagating lasers positioned in the receiver side over the same 100-km SSMF span employed for the signal propagation. The pumping unit at the receiver was designed (in terms of wavelengths and power) to achieve the best compromise between optical gain, noise figure, and gain bandwidth. To this end, an iterative optimization process was developed, encompassing progressive refinements on the equalization profile after each iteration, in order to converge the system to its optimum condition while ensuring the equalized reception of all transmitted channels and avoiding nonlinear degradation. In this process, pumps and channels spectral allocation are initially defined in terms of maximum gain and amplification bandwidth, respectively. Next, the transmitter-side amplifiers are adjusted looking for the maximum gain, followed by the receiver ROPA design based on the received OSNR as optimization metric. Finally, the system's maximum reach and capacity are estimated to meet the required OSNR to receive all transmitted channels. This process resulted in receiver-side pumps coupled two by two in polarization and allocated in the 1450-nm spectral region, providing optical gain through simultaneous DRA and ROPA pumping. Finally, at the receiver, the signal is pre-amplified, demultiplexed, and photodetected by the same transponder employed as transmitter, which will estimate the real-time BER before the forward error correction (pre-FEC).

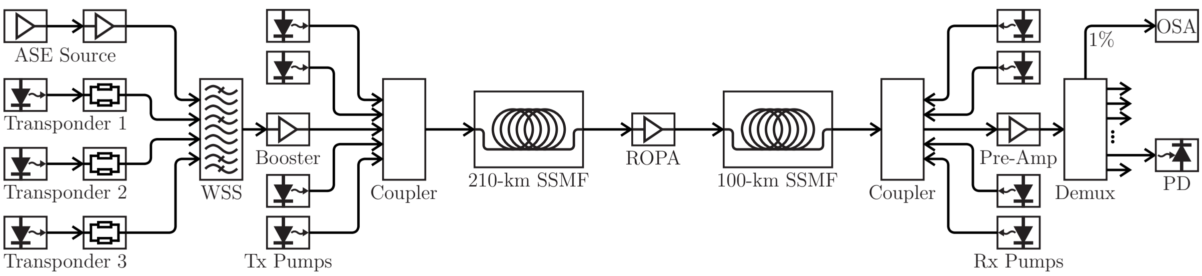

Fig. 2. System setup employing 1st-order DRAs and a ROPA to support the transmission of 128 channels DP-QPSK modulated at 100 Gbps over a 310-km SSMF link.

3. Transmission Results

The pre-FEC BER was characterized in the whole transmission band in steps of 8 channels, as shown in Fig. 3(a), where all channels are below the 1.56×10^{-2} FEC-limit. It is possible to notice that channels at shorter wavelengths have higher penalties, probably deriving from residual nonlinear effects due to its higher propagation maximum power, as shown in Fig. 3(b). On the other channels of the transmission band, the pre-FEC BER variations can be imputed to some deviations on the OSNR equalization (approximately 13 dB per channel at 0.1-nm noise bandwidth). In order to ensure the system proper operation, a bit error rate tester (BERT), connected to a 10-Gbps client interface of the transponder, was employed to measure the BER after the forward error correction (post-

FEC) algorithm. Short duration (1000 seconds, being equivalent to the period for 10 errors to be counted for a 1×10^{-12} BER) and stability tests (over 24 hours) were carried out to certify error-free operation for all tested channels.

Lastly, the experimentally optimized setup was reproduced in a commercial software for optical system simulation. Based on the simulated results, Fig. 3(b) highlights the 128-channel pre-emphasis profile intending to ensure the OSNR equalized reception. However, as previously discussed, due to the transmitter DRA gain profile, the launch power of channels at shorter wavelengths have to be higher, resulting in higher maximum propagated power per channel, as presented in Fig. 3(b), and evinced by the higher BER obtained from the experimental characterization. For the employed modulation format (DP-QPSK) and channel spacing (37.5 GHz), simulated results jointly with system experimental validation indicate that 2.3 dBm per channel is the maximum propagation power allowed to avoid deleterious nonlinearities, which is, together with the received OSNR, crucial parameters for the system proper design and optimization at the simulation stages. Further experimental analysis, ranging the maximum supported number of channels and its spacing, indicate that the denser 37.5-GHz channel grid allows the best system performance in terms of both reach and capacity, even with its lower nonlinearities threshold [9].

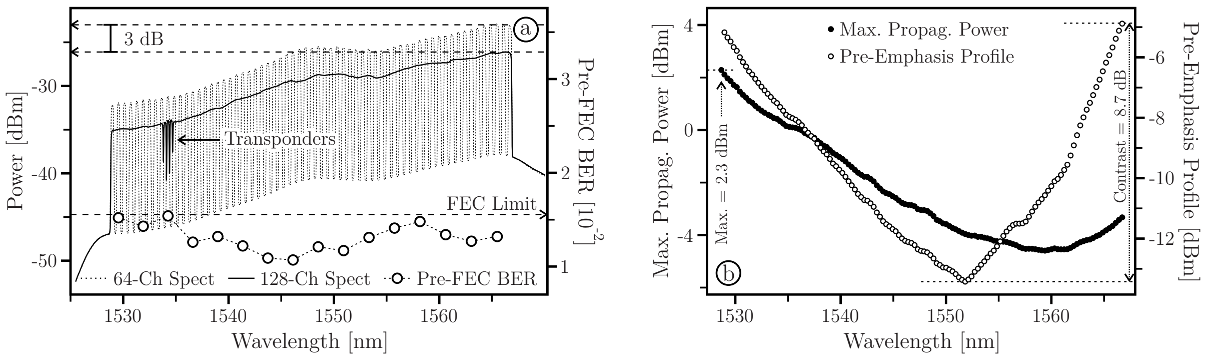

Fig. 3. (a) Experimental results highlighting received spectra for 64 and 128 channels equalized in OSNR and pre-FEC BER per channel. (b) Simulated transmitted pre-emphasis profile and maximum propagation power per channel.

4. Conclusions

A set of 128 channels modulated at a 100-Gbps data rate allocated on the 37.5-GHz flexgrid was unrepeatered transmitted over a 310-km SSMF link, employing only 1st-order DRAs and a receiver-side ROPA to provide optical gain along the spans. The link was designed using an iterative method to optimize the compromise on maximum propagation power per channel, received OSNR, and transmission reach. Due to the commercial maturity and simplicity of 1st-order DRA pumps and SSMFs, the proposed system reduces implementation and maintenance costs, specially when compared with high-order DRA solutions based on special large-effective area and low-loss fibers. The performance, comparable to more complex systems, and cost-effectiveness indicates the possibility for the designed pumping units be adopted in affordable commercial solutions for high-capacity transmission over long-reach unrepeatered links, including the possibility to upgrade the capacity on legacy systems while maintaining most of their existing infrastructure.

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