20.6 Pb/s·km Unrepeatered Transmission without ROPA: UWB SOA Booster and Backward Raman Amplification

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Abstract *Semiconductor optical amplification complemented by backward-propagating Raman pumps enables 100 nm ultra-wideband transmission which, when coupled with wavelength-adaptive modulation and SD-FEC, gives a net throughput of 80.2 Tb/s over a single span of 257.5 km.*

Introduction

Unrepeatered links provide an economical solution for optical fiber systems tailored to connections between remote islands, from a branching unit to the closest coastal landing point, as well as between areas of high inaccessibility in terrestrial systems. One of the main benefits of single-span systems is that they do not require any active in-line components (i.e. repeaters), thus reducing the cost and complexity related to system configuration and eliminating the need for delivering electrical power through the cable. The main challenge of unrepeatered systems has always been simultaneously increasing the throughput and the transmission distance, the two figures being inversely proportional, as dictated mainly by the span loss. As such, low-loss high-effective area fibers, high-power booster at the transmitter, remote optically pumped amplifiers (ROPAs), forward- and backward-propagating Raman pumps have typically been combined to provide sufficiently high gain for covering long spans consisting of multiple hundreds of km[1]-[6]. While these schemes improve the transmission distance, the system's optical bandwidth remains unchanged. Moreover, ROPAs come with an added system complexity, as they require pumping to be delivered from the terminal ends[7],[8]. Further capacity improvements in unrepeatered systems have been enabled by advanced modulation formats[4]-[8]. Probabilistic constellation shaping (PCS) and high soft-decision forward error correction (SD-FEC) coding gains[9], typically proposed for long-distance repeatered experiments to maximize the achievable information rate (AIR) for a target signal-to-noise ratio (SNR), have also recently been introduced to unrepeatered links, enabling the highest recorded throughput to date of 29.2 Tb/s over a single span of 295 km (a capacity-distance product of 8.6 Pb/s·km)[10]. To achieve even higher capacities, with the benefit of significantly reducing the cost per bit, extensive wavelength division multiplexing can provide the solution. To date, most demonstrations of high-capacity unrepeatered systems focused on the C-band[1],[4]-[7], and only a few have targeted the S- and the L-bands[1],[11]. Ultra-wideband (UWB) amplification covering 100 nm bandwidth enabled by custom semiconductor optical amplification (SOA) has recently enabled a record capacity transmission over a 100 km span[12]. When coupled with distributed Raman amplification (DRA), SOAs have enabled larger throughputs over a 3x100 km repeatered setup[13]. In this paper, we leverage on state-of-the art SOAs for seamless UWB pre-amplification covering 100 nm over the S-, C- and L-bands and 2nd order Raman backward-pumping only, greatly simplifying the system design. Without ROPA, we transmitted 247 channels spaced by 50 GHz over 257.5 km of 130 µm² fiber and successfully achieved a net throughput of 80.2 Tb/s using wavelength adaptive modulation and SD-FEC. We achieved the highest capacity-distance product of 20.6 Pb/s·km for an unrepeatered system to date.

Experimental Setup

The experimental setup of the 100 nm wide optical system, using a 257.5 km long unrepeatered transmission link is shown in Fig. 1. At the transmitter side, a 100.4 nm wide optical spectrum ranging from 1514.8 to 1615.3 nm made of amplified spontaneous emission (ASE) noise is generated. The ASE noise spectrum is sent to one input port of an ultra-wideband wavelength selective switch (WSS)[14], configured with a spacing grid of 50 GHz. The WSS exhibits an average insertion loss of 5.5 dB. The generated 100 nm wide optical spectrum is then coupled to a set of three channels. This set contains one central channel made of a tunable laser source (TLS) modulated with a dual-polarization (DP) I/Q modulator driven by a dedicated digital-to-analogue converter (DAC), plus two surrounding channels modulated with a distinct DP I/Q modulator

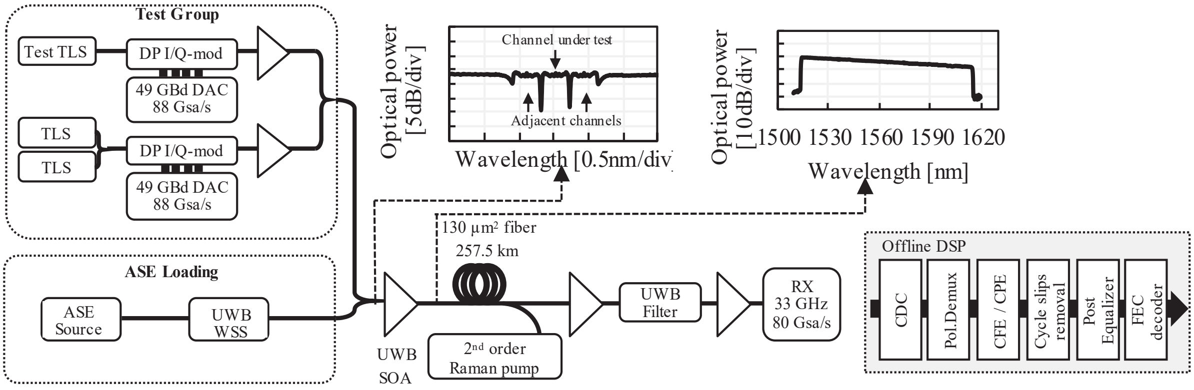

Fig. 1: System setup comprising three modulated channels multiplexed with ASE, boosting SOA at the transmitter, 257.5 km of ULL PSCF and backward Raman amplification at the receiver end.

driven by a second dedicated DAC. The group of channels is iteratively swept across the entire bandwidth covering 247 slots of 50 GHz. Each DAC operates at 88 GS/s and is loaded with a randomly generated sequence at a symbol rate of 49 GBd. Pulse shaping is performed using root-raised cosine pulses with roll-off 0.01 and modulation formats based on DP-PCS-64QAM (with entropies of 5.4 or 4.6) or DP-16QAM constellations are adaptively defined to maximize the information rate, as detailed in section 3.

The optical signal is then sent into an SOA-based UWB amplifier and launched into the optical link, at a total power of 21 dBm. The link is composed of a single span of 257.5 km of Sumitomo ultra-low loss (ULL) pure silica core fiber (PSCF) (130 µm2 effective area) totaling an average span loss of 39.2 dB at 1550 nm. At the end of the link, we utilized four backward Raman pumps at 1365 nm, 1425 nm, 1455 nm and 1494 nm, driven at 2.1 W, 0.6 W, 0.15 W and 0.2 W respectively, such that the second order pumping scheme improves the noise figure compared to the traditional first order pumping. The average Raman on-off gain was approximately 28 dB, typical of unrepeatered links.

At the end of the link, the channel under test is filtered out and pre-amplified before being sent to the coherent receiver, including a coherent mixer, a tunable local oscillator, balanced photodiodes and a 33 GHz bandwidth high speed sampling scope operating at 80 GSa/s. Data sets of 2 million samples are stored on the high-speed sampling scope. Signal processing is then performed offline[9] as outlined in Fig. 1. After chromatic dispersion compensation (CDC), a polarization demultiplexing stage is implemented and followed by carrier frequency and phase estimation (CFE/CPE) preceding a final equalization stage implemented as blind MIMO MMSE channel estimation. The SNR and GMI were computed, accounting for the 2% DSP pilot overhead.

Results

As shown in Fig. 2-a) (red line), the power loss experienced by shortest wavelengths is about 1.3 dB higher than that of longest wavelengths. The observed power loss variation versus wavelength is due to stimulated Raman scattering (SRS) effect and wavelength dependent fiber loss on such a wide optical signal at a launched power of 21 dBm. We determined the fiber loss (dotted line in Fig. 2-a)) by launching the signal at a much-reduced power to avoid the SRS effect. Subtracting the fiber losses from the total span losses, we find that the SRS gain in Fig. 2-a) (right-axis) was approximately 2.5 dB between the extreme ends of the spectrum. To mitigate this effect, we have adjusted the power profile of the modulated channels and the UWB WSS at the transmitter to provide an output optical spectrum with a tilt of 8 dB higher power level on shortest wavelengths as shown in the inset of Fig. 1. Such a pre-emphasis enabled a reduction of the optical signal-to-noise ratio (OSNR) variation of the system.

At the end of the span, the per channel SNR measured from the received symbols varied between 5.83 dB and 12.43 dB, as shown in Fig. 2-b). The SNR profile is predominantly impacted by the 3dB variation in power losses across the 100 nm bandwidth, with additional penalties at the extreme wavelengths, due to transceiver impairments and the SOA bandwidth limitation. Applying three different modulation formats, as depicted by the markers and constellation diagrams in Fig. 2-b), enabled the maximization of the achievable information rate (AIR), depending on the SNR region of operation of any given channel and ensured that error-free decoding could be achieved for that channel and for the given set of selected code-rates. Based on the generalized mutual information (GMI) obtained, which varied between 2 and 4

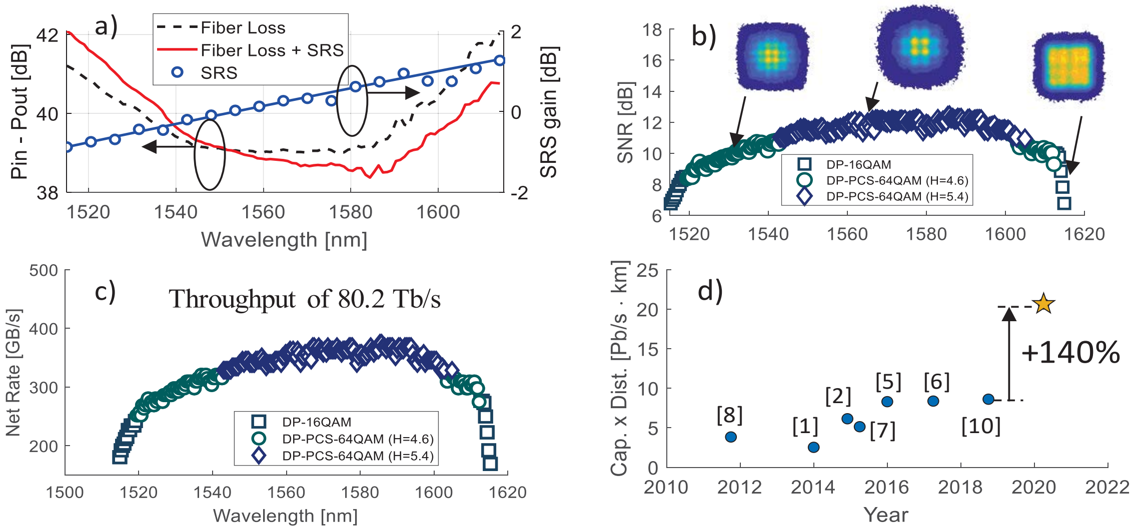

Fig. 2: Measured (a) OSNR equalization, (b) span loss and SRS gain and (c) post SD-FEC channel rates and SNR. (d) Record experimental results over recent years.

b/symbol/pol., and accounting for the 2% pilot tones overhead, a total gross rate of 85.3 Tb/s was achieved. For post-processing, codes from the spatially-coupled low-density parity check (SC-LDPC) family were adaptively selected to implement the SD-FEC on each channel[15], with rates between 0.44 and 0.82. For each channel, we selected the highest rate resulting in error-free transmission. After applying the SD-FEC, the achieved net throughputs per channel varied between 169 Gb/s and 374.6 Gb/s, as shown in Fig. 2-c), resulting in a total net rate of 80.19 Tb/s and a 140% improvement in the capacity-distance product compared to the previous record[10] as depicted in Fig. 2-d). Should the availability of the channel rates be only in 50 Gb/s increments, between 150 Gb/s and 350 Gb/s, the total achievable net throughput would be 74.5 Tb/s.

Conclusions

This paper presented a record transmission experiment demonstrating both the highest capacity and the highest capacity-distance product ever achieved on a single-mode fiber unrepeatered system. Without utilizing ROPAs, a simplified design based on UWB SOAs at the transmitter and receiver ends and only backward-pumping distributed Raman amplification was proposed. The result of 20.6 Pb/s·km presented herein is bringing more than a two-fold improvement compared to the previous record for a similar distance[10]. This record represents the longest single-span transmission with an SOA and was achieved through, on one hand, the interplay between the 100 nm optical bandwidth enabled by the SOAs and, on the other hand, the high net-rates obtained from the utilization of advanced modulation formats (PDM-16QAM/PCS-64QAM) and adaptive SD-FEC codes tailored to each channel.

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