63.2Tb/s Real-time Transmission Through Discrete Extended C- and L-Band Amplification in a 440km SMF Link

D. Le Gac, D. Bendimerad, I. Demirtzioglou, I. Fernandez De Jauregui Ruiz, A. Lorences-Riesgo, N. El Dahdah, A. Gallet, H. Elfaiki, S. Yu, G. Gao, R. Brenot, Y. Frignac, G. Charlet
Huawei Technologies France, Paris Research Center, Optical Communication Technology Lab
dylan.le.gac@huawei.com

Abstract *We demonstrate a 63.2-Tb/s throughput in a 5-span 440-km SSMF link employing real-time 400G 16QAM transponders and fully discrete C- and L-band amplifiers with a total amplification bandwidth approaching 100nm.*

Introduction

The spectral efficiency (SE) of current optical transponders has considerably increased close to the Shannon limit thanks to the use of advanced Digital Signal Processing (DSP) techniques [1, 2]. With only marginal improvements brought by novel DSP techniques expected in the near future, increasing the useful optical transmission bandwidth becomes one of the key solutions to further increase the system capacity of WDM fiber networks.

With system capacity scaling almost linearly with bandwidth, several Ultra-Wide Band (UWB) transmission experiments have been recently demonstrated. In [3], a total of 103nm optical bandwidth covering S+C+L bands over 300km Standard Single-Mode Fibers (SSMF) transmission was achieved by means of Semiconductor Optical Amplifiers (SOAs) and distributed Raman amplification. In [4], a total of 13.6THz was achieved by means of C- and L-band Erbium Doped Fiber Amplifier (EDFA) + S-band thulium-doped fiber amplifiers (TDFAs) for a total transmission distance of 40km.

While the use of S-band becomes attractive for future systems, bandwidth extension to L-band becomes the first step to increase the capacity of current deployed systems mainly based on C-band EDFA technology. While current commercial C-band EDFAs can reach up to 6 THz (48nm), increasing the bandwidth of L-band EDFAs beyond 5 THz remains extremely challenging due to linear and nonlinear noise increase [5-7]. Therefore, other discrete amplification techniques based on Erbium-Doped Tellurite Fiber Amplifiers (EDTFAs) or Discrete Raman Amplifiers (DRAs) have been investigated [8-10]. Besides discrete amplification, the benefits of hybrid distributed Raman plus EDFA for C+L systems are well known in terms of system performance improvement [11-12], however its use is not always convenient due to the inherent additional system implementation requirements and cost. The use of discrete-only amplification is therefore preferred. In [13], we demonstrated WDM transmission covering 100nm C+L total optical bandwidth over a 3-span 220km terrestrial link using discrete-only amplification, and high baud-rate 95-GBaud off-line transponders.

In this paper we demonstrate 63.2-Tb/s throughput over 440-km composed of 5-span SSMF, and 97nm discrete C+L optical amplification. We employ commercial real-time 400 Gb/s PDM-16QAM transponders to approach real system conditions, leading to more strict system design constraints and generally less overall total capacity [15-18]. In addition from our previous demonstration [13] we also apply larger span length (from 80km to 100km leading to 4 dB higher span loss), and double the transmission distance from 220 km to 440 km. By employing SSMF, we avoid the use of high-performance fibers typically not used in the field. This transmission demonstration exhibits one of the highest terrestrial throughput using real-time transponders. The 97 nm total amplification bandwidth is achieved employing commercial 48 nm C-band EDFAs plus extended 49 nm L-band amplifiers. The total bandwidth exceeds by 23 % the ones claimed in product demonstrations in [5] and [19]. This transmission is positioned among previous similar works in Fig.1, with emphasis on wide band transmission, lumped amplification, SSMF fibers, and real-time transponders.

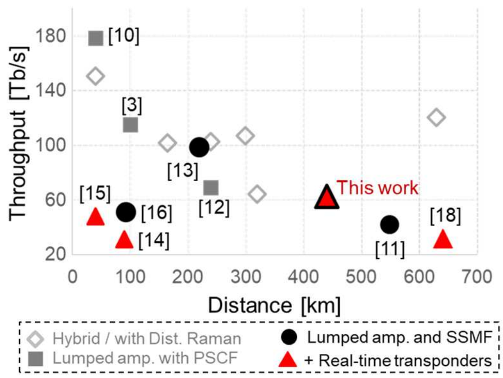

Fig. 1: Positioning in term of throughput and distance.

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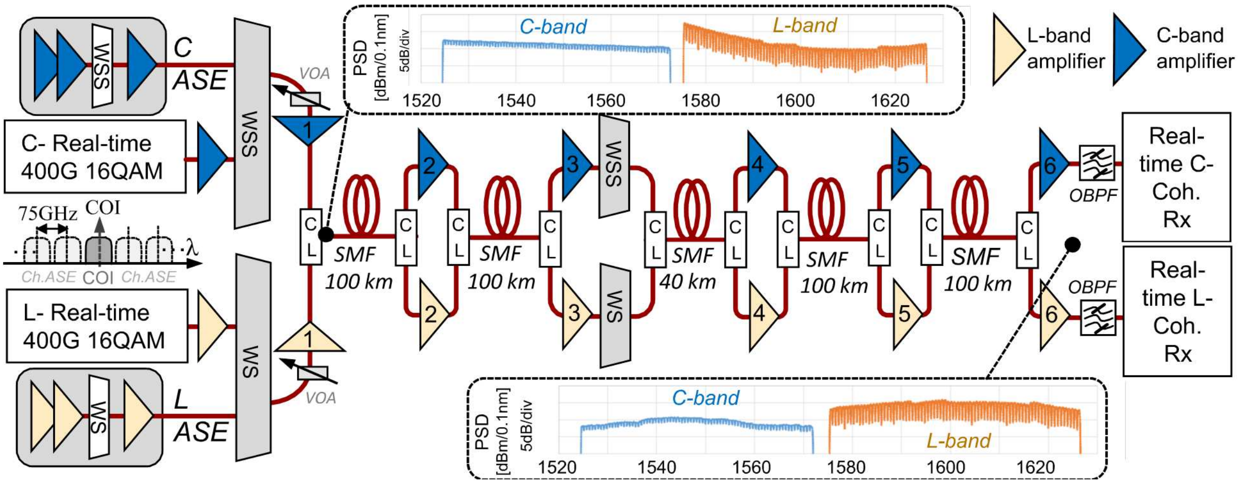

Fig. 2: Transmission system setup.

Experimental Setup

The experimental setup is illustrated in Fig. 2. At the transmitter side, a 48nm amplified-spontaneous emission (ASE) noise source is spectrally shaped by a Wavelength Selective Switch (WSS) to generate 80x62.5GHz ASE-shaped WDM channels over the C band in a 75GHz grid. In the same manner, a 49nm ASE source plus a Wave Shaper (WS) are used to generate 80x62.5GHz ASE-shaped WDM channels over the L band. The channels of interest (COI) consists on two real-time line cards in C and L bands supporting 400 Gb/s PDM-16QAM modulation, which are optically multiplexed with their respective ASE-shaped WDM combs. Both C and L bands are pre-amplified, multiplexed and send to the transmisison line.

The transmission line consists of 4x100km-long SSMF spans. An equalization step after the first 200km based on a WSS for C band and a WS for L-band is used to mitigate power ripples and the generated Raman tilt along the line in order to guarantee a relative flat performance. A complementary 40km SMF section is inserted after the equalization step for a total distance of 440km. At each span, both C and L bands are optically (de)multiplexed through commercial C+L (de)multiplexers with an average loss of ~1 dB each, including connector loss. Commercial 48nm C-band EDFAs and extended 49nm L-band amplifiers compensate for each span loss. The total lauched power into each 100km span is ~24.5dBm. For a total amplification band of 97nm, the generated Raman tilt at each span exceeds 8dB, leading to an average span loss difference between C and L bands of 4.4dB already accounting for the fiber wavelength dependent attenuation coefficient. The resulting amplifier required average gains to compensate for the span loss is ~23.6dB and 19.2dB for C and L bands respectively. Fig. 3 shows the measured fiber attenuation profile for 100 km of SSMF, the computed Raman tilt obtained via solving the Raman Ordinary Differential Equations (ODE), the overall span loss when considering both effects, and the total span loss considering 2dB extra-loss due to C+L (de)multiplexers.

The power profile after each equalization stage and the gain tilt of each amplifier are carefully optimized in order to achieve a relatively flat performance at the end of the 440km line by achieving a proper balance of linear and nonlinear effets across the spectrum.

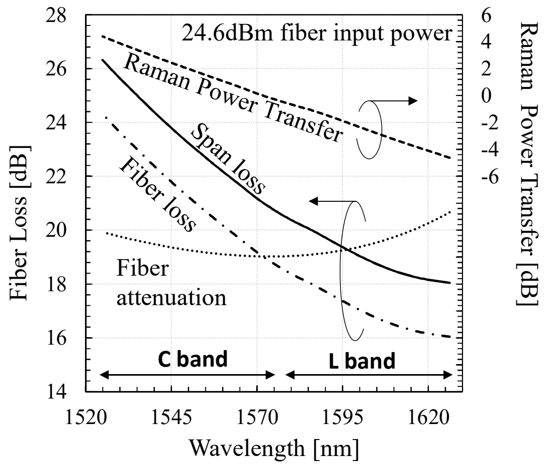

Fig. 3: C- and L-band fiber dependent loss and SRS effect.

At the receiver side, the COIs are demultiplexed using an optical band-pass filter (OBPF) and send to their corresponding real time receivers for Bit-error-rate (BER) measurements. The COIs are sweeped accross the 80 channel slots in C-band and on 78 channel slots in L-band due to transponder limitations. An optical spectrum analyser (OSA) is placed before each OBPF for optical signal-to-noise ratio (OSNR) measurement.

Experimental Results

Fig. 4 shows the output power profiles per channel at the transmitter side (Amp 1), before and after the mid equalization-stage (Amp 3 and Amp 4), and at the receiver side (Amp 6). The optimized transmitted spectrum presents a 5dB tilt over the C-band, while a parabolic shape with a maximum power difference of 7dB is applied to L-band amplifiers. These optimized power profiles guarantee to balance the wavelength dependent span loss including SRS, amplifier un-flat gain profiles, and transmission non-linear effects. The output power profile after the 5th-span presents a maximum power difference of 3 dB over each C- and L-bands.

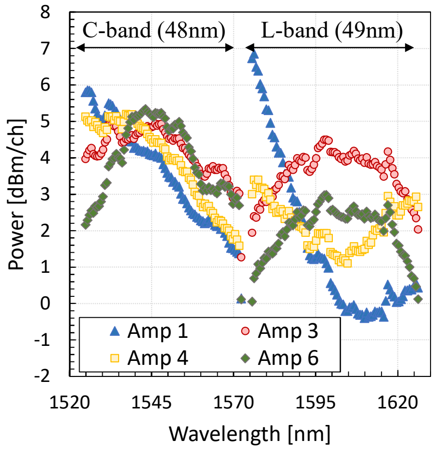

Fig. 4: Power per channel at the transmitter side (Amp 1), before and after the mid equalization-stage (Amp 3 and Amp 4), and at the receiver side (Amp 6).

Fig. 5(a) shows the measured OSNR for 8 and 9 channels distributed along the C- and L-bands respectively. The average OSNR in C-band is 26.5dB while it is decreased to 25.5dB in L-band. The measured BER from the real-time transponder for the total 158 channels is shown in Fig. 5(a). A mean BER of 1.19e^{-2} and 2.47e^{-2} are achieved over C- and L-band respectively, corresponding to a Signal-to-Noise Ratio (SNR) difference of 1.3 dB. The BER for all channels is below the forward-error-correction (FEC) limit of the transponder achieving error-free transmission. The total throughput is 63.2Tb/s.

In order to estimate the achievable capacity employing next-generation transponders based on constellation shaping QAM (CSQAM) formats, we replaced the real-time COI's by an offline transponder based on a 120-GSa/s Arbitrary Waveform Generator (AWG) transmitter, and a 256-GSa/s real-time scope coherent receiver [13]. A CS64QAM signal with 5.5 b/symbol is generated and digitally processed using Python-based DSP algorithms, i.e. chromatic dispersion compensation, 3% pilot-aided 2×2 MIMO equalization, frequency offset compensation and pilot-aided phase estimation. The performance was evaluated in terms of SNR and Generalized Mutual Information (GMI). The measured SNR and GMI for 30 channels across the C- and L-band are shown in Fig. 5b. An average of 15.7dB SNR is achieved for C-band, while it is degraded to 13dB for L-band. This degradation mainly due to the higher noise figure and gain ripples of our extended L-band amplifier. Based on GMI, the total transmitted capacity could be increased up to 55% compared to the real time performance.

Conclusions

We have demonstrated a total transmission amplification bandwidth of 97 nm leveraged by C-band EDFA and extended-L-band amplification. For a 5-span 440-km transmission system, a 63.2-Tb/s total throughput has been achieved using 158 channels based on real-time 400 Gb/s PDM-16QAM transponders with a transmission line design which accounted for the fiber wavelength dependent attenuation and Raman tilt.

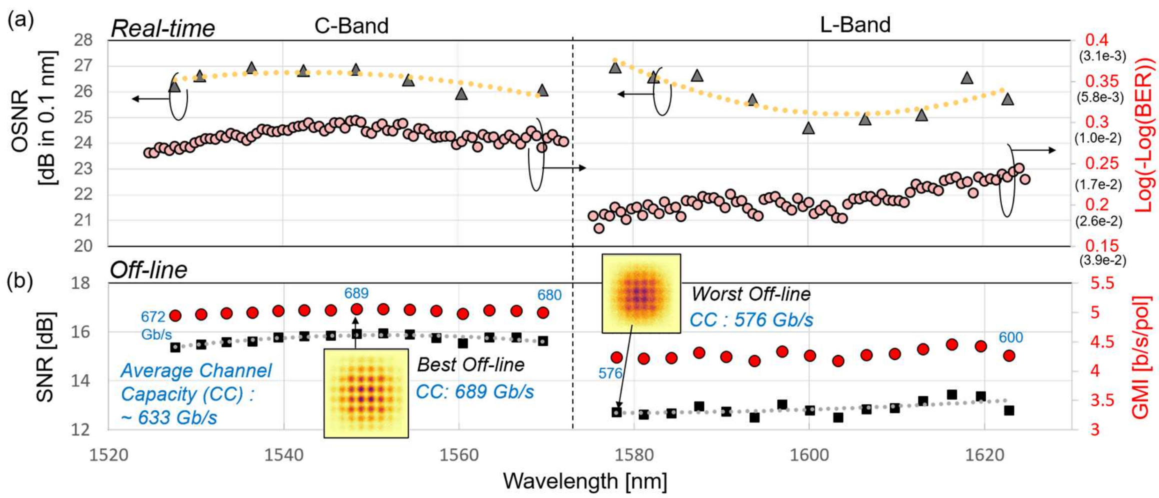

Fig. 5: C- and L- band all channels real-time performances in terms of BER and OSNR (a) on top and some channel offline measurements in terms of SNR and GMI (b).

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