66.8 Tb/s Real-Time C+L Unrepeatered Transmission over 301 km using Forward and Backward Raman Amplification

Ivan Fernandez de Jauregui Ruiz(1), Nurmemet Abdukerim(1), John van Weerdenburg(1), Thomas Gerard(1), F. J. Vaquero Caballero(1), Jonathan M. Buset(1), Lidia Galdino(2)

(1)Infinera Corporation, San Jose, California, USA, (2) Corning Incorporated, Corning Optical Communications, Lakeside Business Village, CH5 3XD, UK. ijauregui@infinera.com

Abstract: We demonstrate record real-time 66.8 Tb/s over 301 km unrepeatered fiber transmission based on commercial 100.4 GBaud PCS-64QAM digital subcarrier-based transponders and commercial 9.6 THz multi-band C+L line system employing forward and backward Raman amplification.

1. Introduction

The capacity of current optical fiber networks has been drastically increased in the last years by the synergy of different technologies. From one side, commercial elastic optical transceivers (EOT) making use of Probabilistic Constellation Shaping (PCS) and soft-decision forward error correction (SD-FEC) codes have allowed spectral efficiency to approach the Shannon limit, while also enabling fine rate tunability to tailor data-rates to the transmission line performance. On the other side, optical transmission bandwidth extension beyond the C-band has become a common practice with commercial C+L systems being widely deployed, and research focusing more on S+C+L bands and beyond [1-2]. Just as for repeated systems, the aforementioned technologies become key enablers to boost the performance of single span unrepeatered systems which provide an effective solution for links where the use of in-line amplifiers is not cost-effective or even not feasible. In these systems, the performance is severely impacted by the high associated span losses that can exceed 40 dB such that the use of ultra-low loss optical fibers and special amplification schemes are typically required. While the use of EOTs is straightforward, extending the transmission bandwidth of these systems beyond the C-band remains challenging, as the Stimulated Raman Scattering (SRS) effect imposes additional amplification requirements and the use of spectral power optimization techniques to counteract the high-performance imbalance between bands.

In this context, several transmission hero experiments have been reported [3-10] (Fig.1a). In particular, 91.59 Tb/s over 234.8 km (21.5 Pb/s·km) covering quasi-continuous 87.2 nm over C+L bands was presented in [3], while 99.35 Tb/s over 257 km (25.6 Pb/s·km) based on continuous 100 nm (S+C+L) semiconductor optical amplifiers was shown in [4]. Both demonstrations employed off-line transceivers making use of high granularity multi-rate FECs allowing data-rate tuning as low as ~0.12 b/symb which is outside the operating point of current commercial EOTs.

In this work, we demonstrate net 66.8 Tb/s transmission over 301 km (20.1 Pb/s·km) employing C+L bands. In contrast to previous works, we employ commercial real-time 100.4 GBaud PCS-64QAM transceivers and a fully commercial optical line system based on standard 39.2 nm (4.8 THz) C- and L erbium-doped fiber amplifiers (EDFA). A typical real-field configuration based on fully integrated reconfigurable optical add-drop multiplexers (ROADM) and a colorless add-drop architecture is considered, together with forward and backward distributed Raman amplification. To the best of our knowledge, this is the highest capacity-distance product reported for an unrepeated link based on commercial system cards and real-time transceivers representing real-field deployments.

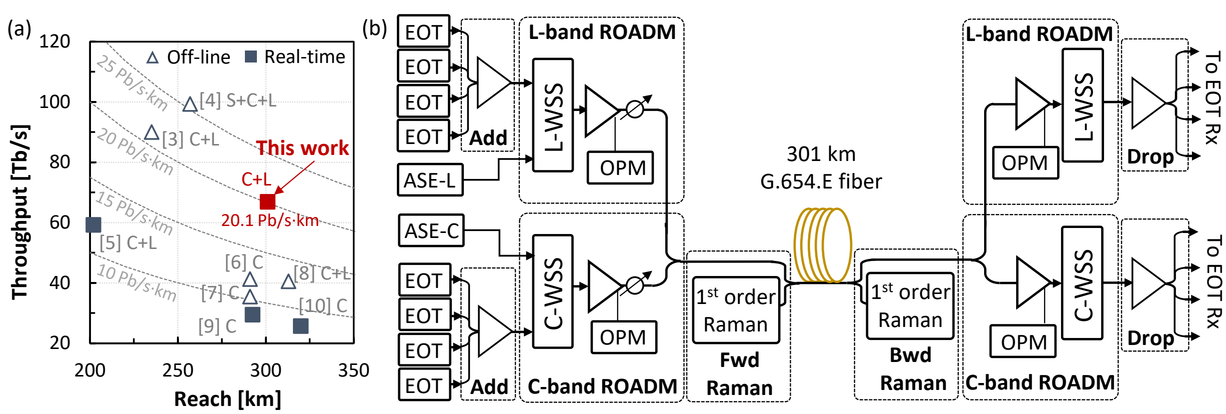

Fig. 1. (a) Recent unrepeated transmission hero experiments above 200 km without remote optically pumped amplifiers (ROPA). (b) Experimental set-up based on C+L commercial optical line system and real-time 100.4 GBaud PCS-64QAM elastic optical transceivers (EOTs).

2. Experimental Set-up

Fig. 1b illustrates the experimental set-up. At the transmitter (Tx) side and for each band, 2 commercial dual-wavelength EOTs are used to generate 4 data channels. Each channel is set to operate at 100.4 GBaud with PCS-64QAM modulation, for which the net data-rate can be selected between 200 to 800 Gb/s in steps of 50 Gb/s (~0.5 b/symb) by PCS entropy tuning. The data channels spaced at 106.25 GHz are combined using a colorless add multiplexer and sent to one port of a ROADM card. A 4.8 THz amplified-spontaneous emission (ASE) noise card is connected to a second port of the ROADM to emulate full loading conditions. The group of data channels and ASE noise are then multiplexed within the ROADM's wavelength-selective-switch (WSS) and amplified by a booster EDFA. The total power for each band is controlled by line-padding variable optical attenuators (VOAs) after each booster. The resulting C- and L-bands are then combined by a band coupler within the C-band ROADM. The WSS attenuation profiles are set to achieve a target Tx power-spectral-density (PSD), which is optimized to compensate for performance ripples. Each group of data channels is swept across the 4.8 THz spectrum in each band for Q^2-factor measurement. A total of 90 slots of 106.25 GHz are measured. The transmission line consists of a single span of 301 km ITU-T G.654.E compliant fiber having a typical attenuation coefficient of 0.148 dB/km, 125 μm^2 effective area, and 20.8 ps/nm/km dispersion at 1550 nm. The resulting C+L total span loss is 46.5 dB. At the span end, a 6 pumps backward Raman card is used to deliver 1st order distributed Raman amplification, while a second Raman card is used for forward Raman amplification to further improve performance. At the receiver (Rx) side, the propagated spectrum is sent to the Rx C-band ROADM, where the L-band is demultiplexed. Each band is then passed through an EDFA pre-amplifier and each group of data channels are filtered by their corresponding ROADM's WSSs. The data channels are dropped through a colorless drop demultiplexer and finally sent to their corresponding transceivers where pre-FEC Q^2-factor and post-FEC errors are measured.

3. Results

Fig. 2a (gray solid line) shows the span loss accounting for fiber wavelength dependent loss and connector losses, leading to an average loss of 46.5 dB and 47 dB in C- and L-bands respectively. An attenuation peak centered at 1583 nm with a magnitude of ~0.6 dB per span (or ~0.002 dB/km) results from the fiber fabrication process. As it will be shown later, the presence of this peak does not cause functional transmission performance impact, either in terms of signal-to-noise ratio (SNR) or achievable net data rate. Fig. 2a (black solid line) shows the span loss including SRS effect for 24 dBm total fiber input, leading to an average loss of 47 dB loss with -2 dB tilt in the C-band, and a flatter loss spectrum of ~46 dB in the L-band with loss slightly increasing for higher wavelengths. The corresponding SRS-induced tilt is -2.8 dB (Fig. 2a dashed line). We start by optimizing forward and backward Raman gains in order to maximize capacity accounting for the discrete available EOT data-rates. First, backward Raman pumps are operated at maximum power (2.1 W) leading to 27 dB and 32 dB average on/off gain in C- and L-bands respectively (Fig. 2b). Due to limited short-wavelength pump powers, this configuration results in a highly tilted C-band on/off gain. However, decreasing high wavelength pump powers in order to achieve a flatter overall on/off gain (e.g. ~25 dB) led to a negligible improvement in the C-band while strongly decreasing L-band performance due to a degraded optical signal-to-noise ratio (OSNR).

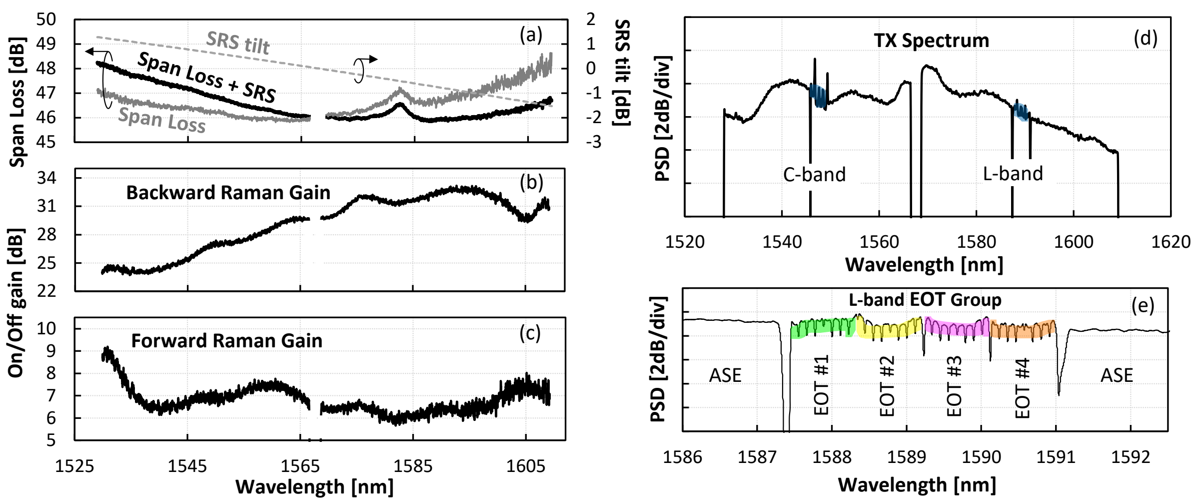

Fig. 2. (a) Span loss without distributed Raman amplification, (b) Forward and (c) Backward Raman on/off gains, (d) Transmitted C+L spectrum with target PSD, (e) L-band EOT test group of 4 real-time digital subcarrier-based 100.4 GBaud PCS-64QAM channels.

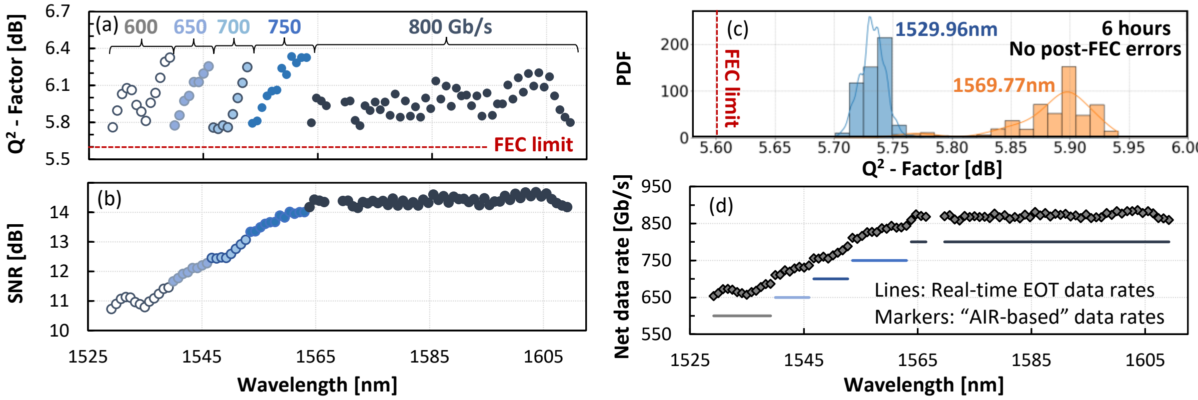

Fig. 3. (a) Pre-FEC Q^2-factor for all 90 measured channels with net data-rates ranging from 600 Gb/s to 800 Gb/s, (b) computed SNR, (c) 6-hours stability test for the first channel in each band, (d) AIR-based and EOT achieved net data rates.

Second, forward Raman pumps are set to achieve a relatively flat on-off gain, which is increased until overall performance is maximized. The resulting on/off gain is found to be ~7 dB across both bands (Fig. 2c). Third, due to the excess performance in the L-band with respect to the highest transceiver 800 Gb/s mode, L-band booster output power is decreased by 1.5 dB with respect to C-band, and a -5 dB tilt is applied to the target Tx L-band spectrum. This configuration, combined with the G.654.E fiber large effective area and lower Raman gain, allows for achieving flat performance across the entire L-band, while boosting C-band performance by reducing SRS. C-band Tx tilt is set to 1 dB found to maximize short wavelength channels. Finally, the Tx PSD is set to minimize Q^2-factor ripples, mainly due to forward Raman induced power ripples. Fig. 2d shows the optimized Tx PSD while Fig. 2e shows a close-up of the L-band data channels. Only the two inner channels are used for Q^2-factor measurement.

Fig. 3a shows the measured pre-FEC Q^2-factor for all 90 channels. Thanks to the use of PCS-64QAM, the channel data-rates are tailored to the link wavelength-dependent performance. All L-band channels and 4 high wavelength C-band channels achieve 800 Gb/s, while C-band performance degrades for shorter wavelengths down to 600 Gb/s. The minimum Q^2-factor of all measured channels is kept 0.15 dB above the FEC limit, leading to a total net throughput of 66.8 Tb/s and a capacity-distance product of 20.1 Pb/s·km. Fig. 3b shows the SNR which is computed from the measured Q^2-factor and the transceiver Q^2 vs SNR theoretical relationships for each mode. A flat SNR of ~14.5 dB is achieved in the L-band, while for the C-band an average of ~12.5dB is achieved with 4 dB tilt mainly due to the highly tilted overall span loss. Fig. 3c shows the histogram of a 6-hour stability test for the first channel in each band (1529.96 nm and 1569.77 nm) where no post-FEC errors were observed. Finally, to quantify the throughput loss due to the coarse available EOT data-rates and residual FEC margins, we estimate the achievable information rate (AIR) by transforming the SNR to the generalized mutual information (GMI) using theoretical SNR vs GMI curves while adding a 1 dB SNR penalty accounting for FEC implementation [11]. The resulting net data rate accounting also for 2% overhead (Fig. 3d) leads to a total throughput of 73.2 Tb/s (22 Pb/s·km), showing a ~10% increase with respect to the real-time EOT available data-rates.

5. Conclusions

We have demonstrated a record of 66.8 Tb/s (20.1 Pb/s·km) unrepeated transmission over 301 km based on commercial real-time 100.4 GBaud PCS-64QAM optical transceivers and an integrated 9.6 THz C+L optical line system making use of forward and backward Raman amplification.

4. References

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