Record 158.4 Tb/s Transmission over 2x60 km Field SMF Using S+C+L 18THz-Bandwidth Lumped Amplification

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Abstract *We demonstrate 158.4 Tb/s GMI throughput over 120km field-deployed SMF multiplexing 6THz-bandwidth S, C and L lumped amplifiers and optimizing channel power pre-emphasis and constellation entropy to maximize fiber capacity. ©2023 The Author(s)*

Introduction

To cope with increasing capacity demand, extending bandwidth of WDM systems is now well recognized as a practical approach from extended C band (6THz) to C+L, now commercially deployed, and potentially S+C+L band systems [1-5] able to further increase the throughput as shown in [2] with 256 Tbit/s over 54 km. Developing large L or S band amplifiers is a real challenge and generally limits recent lab demonstrations to single-short-span systems. Recently we demonstrate 200.5 Tbit/s on 2x100 km pure silica core fiber with Raman amplification [3]. Furthermore, as shown in Fig.1(c), field demonstrations reported maximum 50.8 Tb/s over 93 km on C band system [9] and recent field trial using a 100 nm-bandwidth semiconductor amplifier indicates potential 90 Tb/s over 52 km of deployed fiber [6]. Here we demonstrate a field transmission record with a threefold higher throughput than [9] on 2x60km field deployed SMF from Orange operator network and multiplexing wideband S, C and L amplifiers. Note that we report here a result announced by a press release at 157 Tb/s [7], the results have been boosted to 158.4 Tb/s thanks to offline DSP improvements. The WDM experiment is described and technical details are reported.

Field trial setup

The experimental setup of our S+C+L transmission is shown on Fig. 1(a). On the transmitter side the WDM load of 80 channels spaced by 75 GHz is emulated for each band using an amplified spontaneous emission (ASE) noise source shaped by a corresponding wave-shaper (WS) in S band and wavelength selective switches (WSS) for C and L bands, thus covering a total transmission bandwidth of 18 THz.
The channel of interest (COI) is generated by a

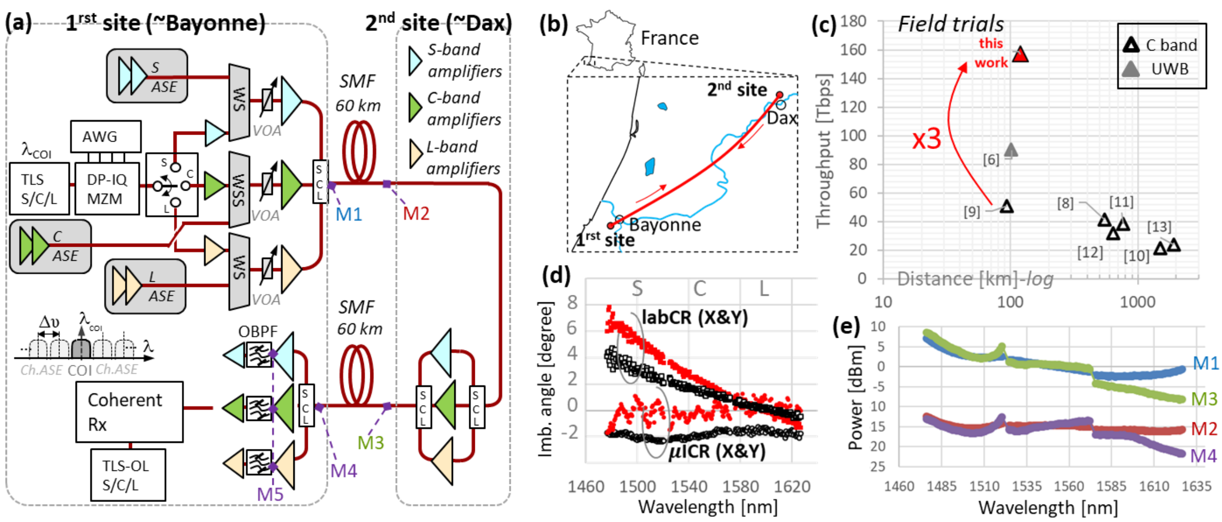

Fig. 1 : (a) field trial setup, (b) field trial sites, (c) field trial transmission positioning from literature, (d) Rx I/Q 90° imbalance for X and Y tributaries, (e) channel power at different location along the transmission.

tunable laser source (TLS) covering all S, C and L bands, modulated using a dual polarization, in phase and quadrature LiNbO3-based modulator (DP-IQ) driven at 70GBd by an arbitrary waveform generator (AWG) operating at 120 GSa/s with 45 GHz bandwidth. Root raised cosine spectrum shaping is applied with a roll-off factor of 0.02. We use here a DP probabilistic constellation shaped (PCS) 64 QAM with 5.5 bits/s/Hz entropy for S and L bands and a DP-PCS-100QAM with 6 bits/s/Hz entropy for C band channels. The entropy of the signal is selected to achieve a normalized generalized mutual information (nGMI) between 0.8 and 0.9 in order to ensure that the probabilistic amplitude shaping (PAS) scheme can be applied with a certain margin. For all cases, QPSK pilot symbol are inserted every 64 symbols for DSP convergence and tracking. COI is then inserted among emulated channels through WSS or WS and each band is amplified with specific booster, combined through S+C+L multiplexer and launched into the fiber spans. The map of the field trial, supported by Orange network in South-West of France is shown on Fig.1(b), transmitter and receiver are in the operator site close to Bayonne, a fiber pair of 60 km SMF is used to send signals to a second site close to Dax, amplify them by demultiplexing and multiplexing S, C and L band and loop them back to Bayonne for performance measurements. Lowest span losses are estimated around 15.5 dB at 1550 nm. Commercial Erbium doped fiber amplifiers (EDFA) are used in C band while fiber-based prototype amplifiers are implemented for S band. In L band we are also using prototype amplifier based on semiconductors as presented in [3], enabling amplification up to 1626 nm as L band EDFA gain is challenging around this wavelength. Spectra are measured at point indicated as M1 to M4 in Fig.1(a) and presented in Fig.1 (e). Channel power pre-emphasis is tuned, following the principle of [15] to target maximum overall throughput. Average total launched power at the entrance of both fiber spans is 25.3 dBm, being distributed as 22.7, 20.5 and 15.9 dBm respectively in S, C and L bands. At receiver side, bands are demultiplexed and COI is filtered out by tunable filter or WSS and launched into a coherent receiver. Due to field trial constraints we are using a micro integrated coherent receiver (µICR) followed by an ADC operating at 103 GSa/s with 3dB-bandwidth of about 33GHz, which limited the back to back SNR to about 16.5 dB, 6 dB less than when using high-speed oscilloscope and 70 GHz photodiodes which were employed in our previous lab demonstration [3]. Still interesting to note that commercial components were suitable over the 18 THz S, C and L band with quite stable characteristics as for example shown by the low Rx I/Q 90° imbalance in Fig.1 (d) labeled µICR; which contrasts to receivers based on discrete components used in [3] labeled as LabCR. All channel performances are estimated using offline processing incorporating chromatic dispersion compensation (CDC), pilot-aided MIMO, frequency and carrier recovery, and post-equalization. Channel performances are estimated using generalized mutual information (GMI) [16] from Rx and Tx offline signal without pilot symbols. We then compute the per channel bit rate B using B=GMI·R·(63/64), R being the Baud rate and the 63/64 ratio account for data symbol ratio.

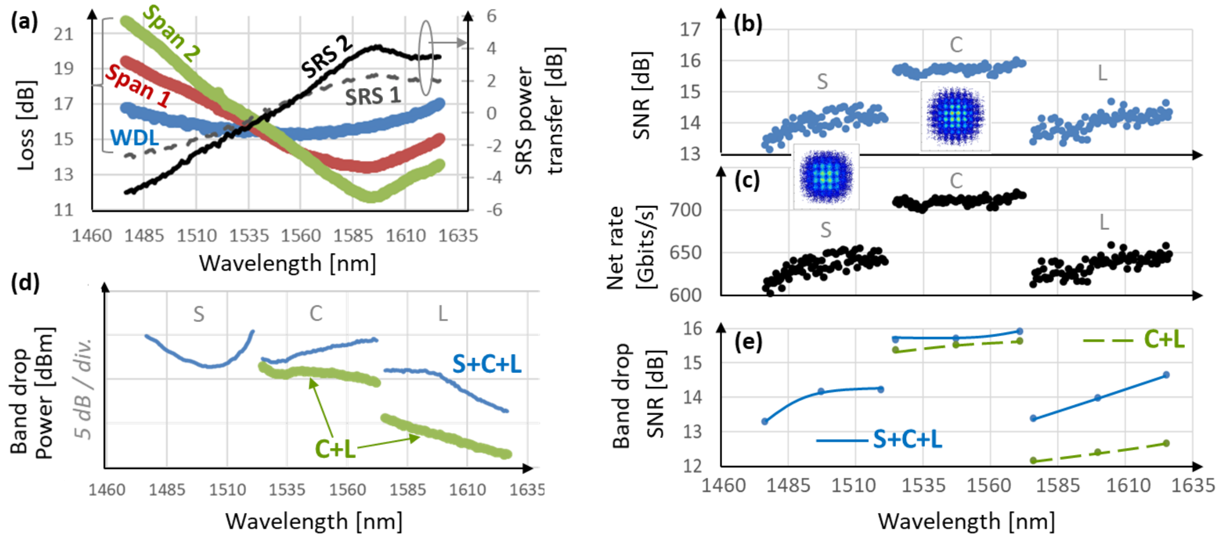

Fig. 2 : (a) Span loss and computed SRS tilt, (b) SNR and (c) net rate for all 3x80 channels, (d) effect of S band dropping on channel power at measurement point M4, (e) Effect of band dropping on channel SNR.

WDM transmission results and performances

Transmission results are presented in Fig.2. Fig.2(a) shows fiber wavelength dependent loss (WDL) with thick blue line, measured the transmitted power of a swept TLS CW light, the overall loaded loss for span-1 (red) and span-2 (green) without including mux losses and computed from OSA spectra of Fig.1(e). From the 2 last losses we also computed the stimulated Raman scattering (SRS) power transfer being 4.9 dB for span-1 (grey dashed line) and 9 dB for span-2 (solid black line). This estimation indicates the presence of a higher lumped losses at the beginning of span-1 in the field trial experiment due to additional fiber interfaces between Tx and line fiber.

Transmission performances results are shown for the 240 channels in Fig. 2(b) in terms of SNR and Fig.2(c) in terms of bit rate per channel from GMI estimations. Examples of 64QAM constellation (used in S and L band) as well as 100QAM are given as insets of Fig.2(b,c). SNR varies from 13.2 to 14.6; 14.4 to 16 and 13.4 to 14.7 dB respectively in S, C and L bands. Corresponding channel bit rate are within 600-650 Gbit/s range in S and L band while reaching a bit more than 700 Gbits/s for C-band channels. S band is affected by higher NF of 6.5 dB for S band amplifier, SRS depletion and additional cross-talk from ASE to COI due to larger WS roll-off when shaping the noise. L-Band performance is penalized by a higher NF of 6.5 dB and the low power setting of L-band OA (6dB below S-Band), selected to avoid too large depletion from S-band that would lead to further performance degradation of S-band. Therefore, our setting choices balance performances across S and L-Band. Record field trial throughput of 158.4 Tbits/s was achieved on single fiber, distributed as 50.78, 56.82 and 50.8 Tb/s in S, C and L respectively. Compared to our press release [7], performance is improved by mitigating static nonlinearity of our trial receiver scheme. As SRS is critical for UWB systems we also investigate the impact of a S band drop (in case of fiber cut in a network for example). Thus, we keep all parameters set for S+C+L transmission and shut down S band. Channel power variations are shown in Fig. 2(d), with thin blue line for the full S+C+L load reference and thick green line for S band drop. Corresponding SNR impacts of this band drop are estimated for 3 channels per band and shown in Fig. 2(e). Here, a drop of S band appears to be impacting significantly with an induced power drop of around 5 dB for L band channels pushing them further in linear regime and inducing a maximum SNR drop by 2 dB at longest wavelengths. This highlight the need for WDM load management in wide band systems.

Conclusions

We demonstrate record throughput of 158.4 Tbit/s on 120 km field deployed fiber of Orange network, thanks to the implementation of a S and L band prototype amplifiers jointly with commercial C band ones leading to a total of 18 THz amplification bandwidth. Commercial components as tunable laser and coherent mixer were shown to cover the S, C and L bands with negligible performance variations. The performance of the 240 channels in the field setup was optimized thanks to an adequate power pre-emphasis and the use of 70 GBd – DP 64QAM or DP 100QAM modulations. We also highlight L-band performance sensitivity to SRS channel power transfer variation due to field lump losses at fiber input as well as potential band drops. This indicates the feasibility of relying on an additional S-band to handle high capacity demand on network links where fiber is rare or rented while taking care of SRS impact.

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