Investigation of Long-Haul S-, C- + L-Band Transmission

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Abstract: We investigate long-distance transmission of a 120nm S+C+L-band signal, observing a small improvement in throughput by launching higher power in S-band. We then measure a fully decoded throughput of 43.5 Tb/s after 10,072 km transmission. © 2022 The Authors

1. Introduction

The ever-increasing demand for enhanced data transmission capacity [1, 2] has inspired investigation of new transmission windows, beyond the C- and L-bands widely in commercial optical fiber communications [3]. Several transmission demonstrations have recently shown that new amplifier technologies enable the use of the S band to significantly increase the transmission capacity over one or a few fiber spans [4-8]. Further, recirculating transmission of an S-, C-, + L-band signal was demonstrated over 3,001 km using polarization-division-multiplexed (PDM)-16-quadrature-amplitude modulation (QAM) modulation [9], however, the feasibility of extending S-band transmission to trans-oceanic distances is yet to be explored.

Here, we address this by investigating transmission of a 120 nm S-, C- and L-band signal up to distances of 10,072 km. In a recirculating transmission loop based on a 92.4 km standard single-mode fiber (SSMF) span, we transmit 552 x 24.5 GBd, 25 GHz spaced, PDM quaternary-phase-shift keyed (QPSK) channels from 1487.8 nm to 1608.33 nm using a combination of Erbium and Thulium doped-fiber amplifiers (E/T-DFAs) and distributed Raman amplification. We compare the transmission performance at 6,098 km for different per-band launch powers**,** observing a small gain in data throughput in a subset of 30 equally spaces channels when higher total launch power is used for S-band channels. Finally, for the launch power configuration measured with the highest average data rate, we measure the achievable data-rate of all 552 channels at distances up to 10,072 km. We use both generalized mutual information (GMI) and LDPC decoding to estimate total data rates of 46 Tb/s and 43.55 Tb/s, respectively, at the longest distance. These results show the potential for wideband signal to enhance data rates in long-haul fiber transmission.

2. Experimental Set-up

Fig. 1 shows the measurement set-up comprising a non-measurement band of dummy channels and a sliding 3-channel test band in which a test-channel and two, 25 GHz spaced, neighbor channels were generated before recirculating transmission. The sliding test band consisted of a central test-channel surrounded by two neighbor channels generated by narrow (<10kHz) linewidth tunable lasers (TLs). Before modulation, the test-band channels were amplified in C-/L-band EDFAs or S-band TDFAs. The TDFAs had an output power >19 dBm and noise figure below 7 dB. Test and neighbor channel modulation was performed in two dual-parallel Mach-Zehnder modulators (DP-IQ) driven by four arbitrary waveform generators (AWGs) operating at 49 GS/s. These produced 24.5 GBd, root-raised cosine shaped, PDM-QPSK signals with a roll-off of 0.01 based on 2^{16}-1 bit pseudo-random binary sequences. The dummy wavelength channels were generated from amplified spontaneous emission (ASE) noise, the spectrum of which was flattened using band-specific optical processors (OPs) and further amplified in the appropriate T/E-DFA. The OPs were also used to carve a movable notch in the dummy channel spectrum to accommodate the current test-band before the both were combined in a power coupler.

Recirculating transmission was achieved using acousto-optic modulator (AOM) based switches to gate the input and recirculating signals. After the load AOM, a 10dB power coupler split signals for recirculation and reception. The recirculating path contained an amplification stage before a 92.4 km span of SSMF. After each DFA before the fiber, variable optical attenuators (VOAs) were used to set the total launch power of each band. After fiber transmission, 10 counter-propagating Raman pumps were added with an optical circulator on the S-band path. The pump wavelengths and powers were 1410.8 nm and 1417.5 nm, with 80 mW, and 1424.2nm, 1431nm, 1437.9 nm, 1444.8 nm, 1451.8

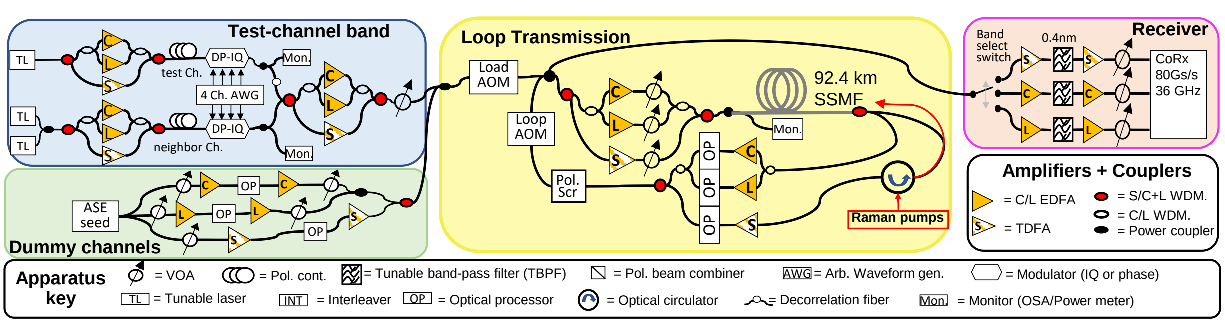

Fig. 1 Experimental set-up used recirculating transmission of >120nm bandwidth (1487.8 nm to 1608.33 nm) signal

nm, 1458 nm, 1466 nm and 1473.2 nm with 40 mW. Also in the loop was a further amplification stage to compensate other loop components which included an additional OP in each band for spectral flattening, a polarization scrambler, and a second AOM switch. The OPs were programmed to target a flat power spectrum at the fiber input for each band.

In each band, the receiver path consisted of amplification stages on either side of a 0.4 nm tunable band pass filter (TBPF) centered on the test-channel with a VOA for power adjustment. A coherent receiver (CoRx) detected the signal using a 60 kHz nominal linewidth local oscillator (LO). The signals were acquired by an 80 GS/s real-time oscilloscope that stored traces for offline processing. This consisted of stages for resampling to 2 samples per symbol and normalization, followed by a time-domain 2 x 2 MIMO equalizer. The equalizer taps were initially updated using a data-aided least-mean squares algorithm, switching to a decision directed algorithm after convergence. Carrier recovery was performed within the equalizer loop. The throughput of each wavelength channel was both estimated from the GMI and independently assessed using LDPC codes from the DVB-S2 standard as previously performed in [7]. To allow for rate-flexibility, code puncturing was used to achieve a code-rate-granularity of 0.01. Code-rates were swept using at least 100 code words per channel until meeting a bit error rate (BER) below 5×10^{-5} including an additional 10% margin. Below this BER, it was assumed that a 1% overhead outer hard-decision code [10], could remove any remaining bit errors.

3. Results and Discussion

The basic characteristics of the Raman amplified fiber span are shown in Fig. 2(a). The flattened S-, C- + L-band input signal (red), in this case launched at 15 dBm/band, is tilted at the fiber output (black) by the combination of stimulated Raman scattering (SRS) and the fiber loss profile (Dashed grey, right-axis). The addition of the Raman pumps compensates some of the fiber loss giving the bulged profile shown in blue. This combination of wavelength dependent losses and gain combined with SRS during transmission and the individual DFA gain profiles and noise figures (NFs) makes determining the optimum launch power strategy for long-distance recirculating transmission a complex problem. To investigate this experimentally, we measure the data-rates of 30 wavelength channels, equally spaced across the transmitted spectrum for different launch power (LP) combinations between the 3 bands at a medium distance of 6098 km. In each case, the loop OPs adjusted the gain spectrum, targeting a flat spectrum within each band at the input to each fiber span. Figure 2 (b) shows the measured data rates, estimated from GMI of the 30 PDM-QPSK channels for 3 cases with equal per-band LPs of 15dBm, 17 dBm and 19 dBm in each band. Evident from Fig, 2 (b) is that changing equal per-band LP has only a moderate impact over this range with 91.65 Gb/s average data rate for 15 dBm compared to 89.5 Gb/s at 19 dBm/band LP. Next, we considered various combinations of independent per-band LP from 13 to 19 dBm. For clarity, of the combinations investigated, the 2 cases with the highest average data-rate together with the same 15dBm equal LP measurement are shown in Fig. 2(c). Although the increase in average

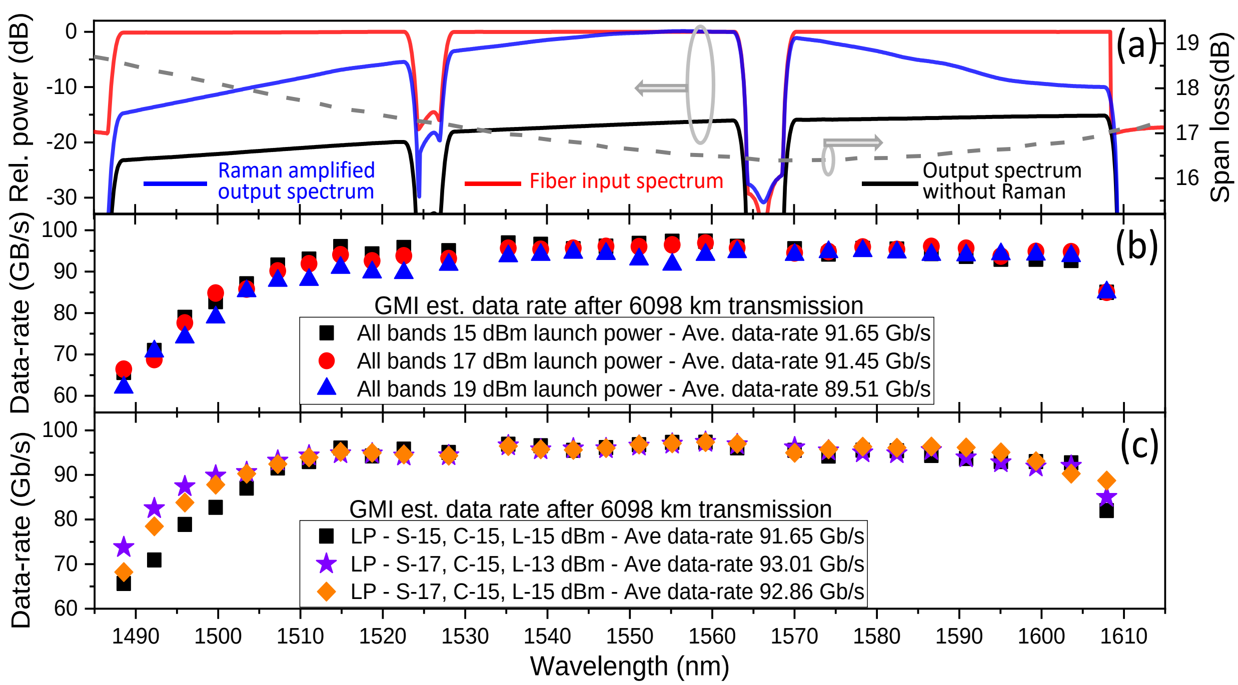

Fig. 2 (a) Left-axis - S-, C- and L-band signal at input (red) + output (black) of first fiber span with Raman amplification profile (blue). Right-axis span loss of 92.4. km fiber (b) GMI estimated data-rate of 30 channels for 3 equal per-band LPs and (c) data-rates comparing unequal per band LPs with equal 15 dBm/band measurement

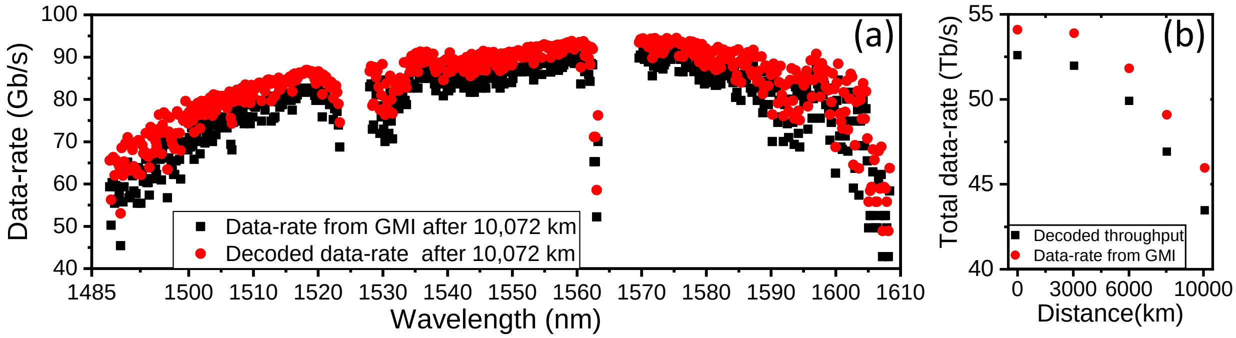

Fig. 3 (a) GMI and LDPC decoded data-rates for 552 received PDM-QPSK channels from 1587.8 nm to 1608.3 nm after transmission over 109 fiber spans totaling 10,072 km and (b) data-rates at intermediate distances

data rate is again small, Fig. 2(c) suggests that some gain in the achievable data rate of S-band channels can be obtained by increasing the relative launch power of S-band channels compared to C and L-band LPs.

Finally, the overall limits of the transmission system were investigated by extending the transmission distance for the launch power combination observed to have the highest average data rate. A summary of the transmission performance at a distance of 10,072 km is shown in Fig. 3(a). The overall shape of the curve resembles the Raman amplified power profile shown in Fig. 2(a), suggesting that the reduced ASE accumulation of the channels with the lowest effective loss between the DFAs before and after the transmission span leads to the highest data rates, with an additional smaller impact of the individual DFA gain profiles. There is also a large variation in data rates between neighboring channels, particularly at the edges of S-, and L-bands that is believed to arise from small ripples in the transmitted optical spectra, which accumulate after multiple passes through the loop components. The total throughput after decoding was 43.5 Tb/s, comprising 13.7 Tb/s from 189 S-band, 15 Tb/s from 178 C-band and 14.8 Tb/s from 185 channels in the L-band. The decoded total was approximately 5.7 % lower than the GMI estimated throughput of 46 Tb/s. Figure 3 (b) also shows the combined data rate of the back-to-back (B2B) wideband signal and after distances of 3050 km, 6006 km, 8039 km and 10072 km, showing throughput may be simply traded with distance and offering the prospect of longer transmission distances.

We note that there remains large scope for further optimization of the investigated transmission system. Whilst the presence of the S-band channels prevents higher wavelength Raman pumps to amplify the high L-band wavelengths, it may be possible to adopt lower wavelength pumps to improve the performance of low wavelength S-band channels. Better optimization of Raman pump powers is likely to provide a more even Raman amplification profile leading to more equal data-rates. Indeed, subsequent measurements revealed flatter gain by individually adjusting the power of each pump. Given the increased fiber loss at the edges of the spectrum, it is also possible that overall throughput could be increased by adopting a shorter fiber span and the impact of loop component loss could be reduced by using multiple fiber spans per recirculation. Nevertheless, these results show the potential of wideband signals to enable increased data rates in long-haul transmission.

4. Conclusions

We have investigated long-distance recirculating transmission of a wideband signal covering >120nm across S, C and L- bands, amplified with a combination of Thulium and Erbium doped fiber amplifiers and distributed Raman amplification. Signal quality measurements of 30 of the 552 x 24.5 GBd PDM-QPSK channels, equally spaced across the transmitted spectrum, showed a small dependance on launch power with the highest GMI estimated data rates achieved with higher relative launch power for S-band channels. Finally, all 552 channels were received at distances up to 10,072 km with the total GMI estimated data rate being and 46 Tb/s and a decoded data rate of 43.5 Tb/s.

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