52.1 Tb/s C-band DCI transmission over DCI distances at 1.49 Tb/s/λ

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Abstract *We report on a DWDM DCI transmission system relying on highest per channel symbol rate of 1.49 Tb/s at 128 GBaud. We compare transmission over G.652 and G.654.E fiber and report a new capacity record of 52.1 Tb/s for C-band transmission.*

1. Introduction

The unabated network traffic growth justifies the need to continuously increase optical transport capacities [1], while simultaneously reducing the cost and the power consumption per transmitted bit. As we have exhausted the degrees of freedom to modulate a lightwave, the main two levers to reach this goal are increasing bitrates per carrier and increasing parallelism in wavelength and space [2]. The former is obtained by increasing the symbol rate and/or by increasing the average information conveyed per symbol. While bitrates per carrier beyond 1 Tb/s have been demonstrated in research [3-6], commercial systems delivering 800 Gb/s per carrier are now being introduced [7,8].

In addition to cost savings in terms of components count, faster signalling rates offer other important advantages such as better utilization of the optical spectrum due to the frequency response of multiplexers. Regardless of the filter profile of mux and demux devices, be it Gaussian or flat-top, they naturally exhibit a guard band of about 10 GHz between two adjacent mux/demux passbands. More guard bands, i.e. multiplexing more channels, reduces the usage of the optical spectrum to convey information. Furthermore, multiplexing fewer channels requires less ports in mux/demux devices, reducing the complexity of the frequency parallelism. In spite of these advantageous in WDM transmission, high symbol rate systems are more difficult to implement due to the high electrical bandwidth requirements of the underlying components. This alone also leads to lower electrical voltages driving the electro-optic transducers after applying spectral pre-emphasis to flatten the entire transmitter's response, which in turn leads to higher insertion loss of CW light passing through a dual-polarization IQ modulator biased at null. Nevertheless, a comparison of the WDM transmission rates reported in the literature (cf. Fig. 1.) shows an overall advantage for the high symbol rates. In these experiments, the WDM grid ranges from 33 GHz to 137.5 GHz and the symbol rates from 32 GBaud up to 128 GBaud. The highest number of carriers was 138.

In this work we demonstrate a C-band WDM transmission system targeting DCI-type distances operating on a high symbol rate of 128 GBaud per carrier, which was recently used to demonstrate a record single carrier rate of 1.52 Tb/s [9]. We transmitted 35 of such channels on a 137.5 GHz grid. After transmission over 81 km of G.654.E fiber (Corning® TXF® fiber) we achieved a total bitrate of 52.1 Tb/s, reducing to 50.7 Tb/s after 129 km. We demonstrate reach gains of 24 km when applying G.654.E fiber compared to G.652 fiber at same total bitrate. To the best of the authors knowledge, this is the highest bitrate transmitted in the C-band, at the lowest number of carriers to achieve the rate.

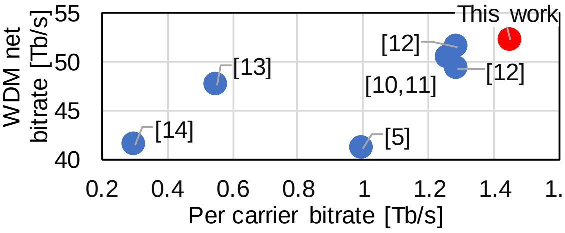

Fig. 1. Reported WDM net bitrates vs. per carrier bitrate. The red marker shows this work.

2. Experimental setup

The experimental setup is shown in Fig. 2. The transmitter actually consists of 2 transmitters, one for the modulation of the channel under test (CUT) and one for the modulation of the other 34 WDM channels. The CUT is swept through the 35 channels and we evaluate its performance at every spectral position. Both transmitters rely on the same two DACs sampling 128 GSa/s, each having a differential output. The 'p' output of the two DACs modulates the CUT, and the 'n' outputs serve to bulk-modulate the other 34 channels. All four differential outputs are coupled to driver amplifiers before being applied to their respective

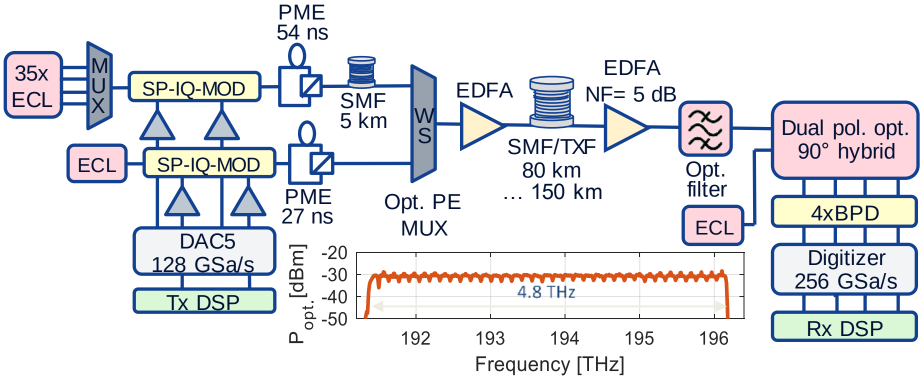

Fig. 2. Experimental setup of 36 channel WDM experiment. The inset shows the optical spectra allocating 4.8 THz in total.

IQ modulator input. Digital pre-distortion (DPD) is applied to compensate the combined frequency response of the DAC and driver. 34 external cavity lasers (ECLs) are multiplexed before being bulk-modulated, and another ECL serves as the CUT. Dual polarization is emulated after both IQ outputs, using delay-and-add interferometers of 27 ns and 54 ns delay, for the CUT and the bulk-modulation branches, respectively. The bulk-modulated signal is delayed with respect to the CUT signal by 24 µs (5 km of SMF) to decorrelate the two branches. The same 5 km spool also serves to decorrelate neighbouring WDM channels by about 85 ps, equivalent to close to 11 symbols at 128 GBaud. The 3-dB bandwidth of the two single-polarization IQ modulator is 41 GHz with a slow decay down to 64 GHz. The response of the IQ modulators is not compensated by the DPD but rather by setting a "M-shape" filter response for each channel in the multiplexing device (WaveShaper 4000s).

For transmission we generated a random bitstream followed by a distribution matcher to probabilistically shape a 256QAM format to an entropy of 7.5 bits/symbol [15-17], which has been identified as optimum entropy in recent experiment [8]. The 2^{15}-symbol-long waveform is repeatedly played back by the DACs.

The WaveShaper not only compensates for the modulator roll-off but also equalizes the per-channel power during multiplexing. The 35 channels spread over 4.8 THz of total optical bandwidth. Thanks to the high symbolrate of 128 GBaud, 93% of the total optical spectrum is occupied by information bearing signals (symbolrate/channel-grid), compared to only 89% for the previous record relying on 100 GBaud [10]. Note that in todays commercial systems operating at 64 GBaud on a 75 GHz grid, the spectral occupancy is only 85%.

After multiplexing, the signal is amplified in a 2-stage EDFA allowing adjustment of both the gain and the gain tilt, delivering up to 22 dBm. For transmission we apply a single span of TXF fiber (G.654.E) ranging from 82 to 150 km in length, or one span of 80 km standard SMF (G.652)

In the receiver we first select the CUT by properly tuning the optical filter and the local oscillator (LO). The CUT and the LO are combined via a dual-polarization 90° optical hybrid whose 8 outputs go to 4 balanced photodetectors. The 4 RF signals are real-time sampled at 256 GSa/s and stored for offline processing. State-of-the-art coherent DSP is applied at the receiver. The performance is assessed in terms of mutual information (MI) or generalized mutual information (GMI). Finally, FEC decoding is applied using variable rate LDPC codes yielding the maximum net bitrate [18,19].

Experimental results

First, we optimized the launch power for the different fiber types and lengths. Fig. 3 shows the achievable total bitrate of all channels as a function of the launch power. Using 82 km TXF fiber, we observed a maximum bitrate at 21 dBm. For longer lengths of TXF, the highest bitrate shifts to higher launch powers, higher than what can be delivered by the EDFA for 129 km and 150 km. Consequently, the optimum linear/nonlinear balance is not reached for these distances and the waveform propagates more in the linear regime. When using 81 km of SMF, the optimum launch power is 20 dBm, which is 1 dB lower compared to TXF fiber over a similar distance.

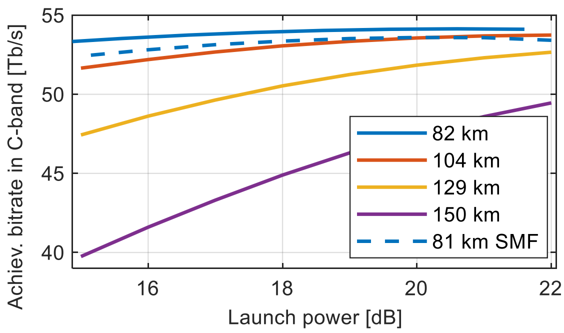

Fig. 3. Achievable bitrate in C-band versus launch power for transmission over TXF fiber over different distances.

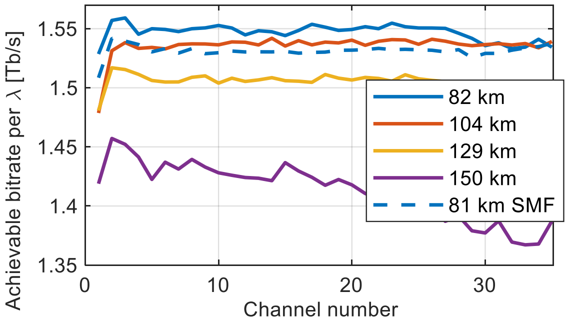

Fig. 4. Achievable bitrate per l for optimum launch power at each transmission distance over TXF fiber.

In Fig. 4 we are showing per-channel achievable bitrates with excellent uniformity across channels over a typical DCI distance of 80 km, thanks to the flat gain profile of EDFAs. At larger distances the performance degrades from the smaller input power presented to the receiver EDFA, which not only increases the ASE noise but also affects the output spectrum profile, as the EDFA gain tilt is input signal power dependent. Even in this regime we observed small variations in the achievable bitrate between carriers of 80 Gb/s, corresponding to a variation in SNR of 0.9 dB.

For the optimum launch power of each fiber type and length, we FEC decoded the received data after DSP. The average net bitrates are plotted against the OSNR, calculated using the received power and the EDFAs noise figure (cf. Fig. 5.). Note that the optical noise mainly stems from the receiver EDFA only, while additional noise sources mainly stem from the transponder. For 80 km fibers, we see a ~4 dB advantage in OSNR for TXF fiber versus SMF due to the increased launch power and the lower attenuation of TXF fiber. The average net bitrate for TXF fiber is 17 Gb/s higher compared to SMF.

For longer transmission distances, we observe a small degradation of bitrate up to 129 km, decreasing more abruptly after 150 km. Furthermore, the bitrate achieved after 81 km of SMF can be achieved at 1.5 dB lower OSNR using the TXF fiber, which we attribute to the lower nonlinear degradation as well as lower fiber losses. For comparison, we plotted the net bitrates for a single carrier experiment in back to back. We observed an excellent agreement to the DWDM experiments up to a net bitrate of 1.45 Tb/s per λ, which is due to negligible linear and nonlinear cross talk from neighbouring channels. Beyond 1.45 Tb/s per λ in DWDM, we see an increasing deviation from single channel performance due to additional noise sources originating from dense wavelength division multiplexing.

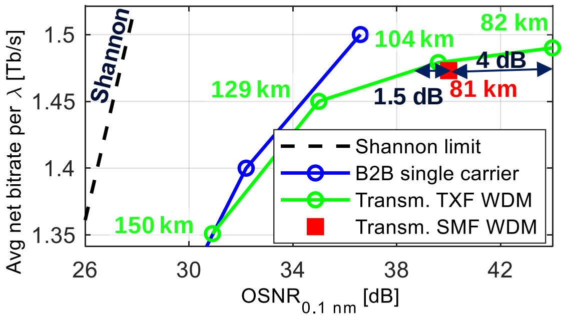

Fig. 5. Average net bitrate after FEC decoding versus OSNR. The OSNR was calculated from received power and EDFAs noise figure.

Finally, we analyze the net bitrate as a function of the transmission distance (cf. Fig. 6.). For the same net bitrate of 51.6 Tb/s, TXF fiber allows for a transmission distance improvement of 24 km compared to SMF fiber. The maximum capacity for a DCI-type transmission distance of approximately 80 km is 52.1 Tb/s. The corresponding spectral efficiency is 10.85 bits/s/Hz. Although the information rate per channel is reduced by more than 9% compared to previous experiments [12] the total capacity reported herein outperforms the previous record by 0.6 Tb/s. Transmission over longer TXF fiber spans of 104 and 129 km leads to small degradations of the net bitrate thanks to the fiber's superior characteristics. At 129 km, we observed a degradation of 1.2 Tb/s only.

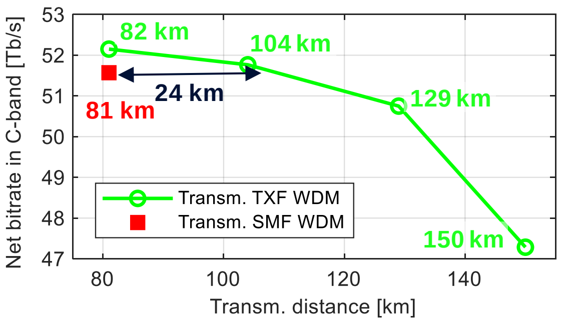

Fig. 6. Net bitrate in C-band versus transmission distance for SMF and TXF fiber transmission.

Conclusions

We implemented a high capacity DWDM transmission system using 35 carriers at 128 GBaud on a 137.5 GHz grid. Thanks to the excellent performance of the transceivers, the TXF fiber, and tighter and higher usage of the C-band, we outperformed recent C-band capacity records to mark a new one at 52.1 Tb/s.

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