72.64 Tb/s DWDM Transmission over 100 km G.654D Fiber Using Super C-Band Erbium-Doped Fiber Amplification

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Abstract: We report a record of 72.64 Tb/s WDM transmission at 12.29 bits/s/Hz over 100 km G.654D fiber. Super C-band EDFAs with 6 THz gain spectrum are used to transmit 43 130 GBaud DP-PCS256QAM channels.
 OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications.

1. Introduction

High-capacity data transport between data centers is a vital need in enterprises to support the ever-growing need for high-bandwidth applications such as video transport, data backup and cloud services. In fact, the role of data centers has rapidly evolved over the last few years from offering basic storage services to providing full-scale connectivity, storage, and disaster recovery. Large data centers today are building high-end dense wavelength division multiplexing (DWDM) optical network solutions to transport up to 400 Gb/s Ethernet services per channel. In order to ensure sufficient connectivity in future, constant evolution in research and standardization of high-capacity optical transmission systems is required. Current standardization effort toward 800 Gb/s solution is ongoing in OIF [1] and IEEE 802.3 [2], while DWDM solutions delivering beyond 1 Tb/s are still in research and development phase.

Recent DWDM aggregate capacity records in C-band or extended C-band using a single optical line system are shown in Fig.1(a). In [3], 41 channels each carrying 96 GBaud dual-polarization (DP) probabilistic constellation shaping (PCS) 256-ary quadrature amplitude modulation (QAM) were transmitted over 100 km ultra-low loss fiber (ULLF) achieving 41 Tb/s DWDM capacity using 4.1 THz DWDM spectrum (spectral efficiency (SE)=10 bits/s/Hz). In [4], 40 channels with 100 GBaud DP-PCS256QAM were transmitted over 93 km and 2×93 km field-deployed standard single-mode fiber (SSMF) achieving 51.5 Tbit/s (SE=11.44 bits/s/Hz) and 49.2 Tbit/s (SE=10.94 bits/s/Hz) DWDM capacity, respectively. Reducing the modulation format to 100 GBaud DP-PCS64QAM for these two links 45.93 Tbit/s (SE=10.2 bits/s/Hz) and 45.1 Tbit/s (SE=10 bits/s/Hz) DWDM capacities were also reported in [4]. In [5], the same 93 km SSMF link as in [4] was used to demonstrate 50.8 Tb/s DWDM capacity at SE=11.29 bits/s/Hz. With respect to [3], in [4] and [5] the DWDM spectrum was extended to cover 4.5 THz (40 channels at 112.5 GHz channel spacing). In [6,7], 35 channels with 128 GBaud DP-PCS256QAM were transmitted over 80 km ULLF and 48 km field-deployed SSMF achieving 52.1 Tbit/s (SE=10.85 bits/s/Hz) and 54.5 Tbit/s (SE=11.29 bits/s/Hz) DWDM capacities, respectively. For these two experiments the spectral occupancy slightly exceeded 4.8 THz. In [8], 34 channels with 130 GBaud DP-PCS400QAM and DP-PCS256QAM were transmitted over 96.5 km of field-deployed SSMF achieving 55.7 Tbit/s (SE=10.92 bits/s/Hz) and 56.5 Tbit/s (SE=11.08 bits/s/Hz) DWDM capacities using 5.1 THz spectrum. The triangle marker in Fig. 1(a) shows the DWDM aggregate net bitrate that we report in this paper.

By extending our previous work [8], we report a record DWDM transmission in a laboratory experiment over 100 km of ULLF compliant with ITU-T G.654D. With an average per-carrier net bitrate of 1.69 Tb/s we obtained a total DWDM capacity of 72.64 Tb/s with SE=12.29 bits/s/Hz. To the best of our knowledge, this is the highest C-band aggregate net bitrate utilizing 6 THz super C-band Erbium-doped fiber amplifiers (EDFAs) [9].

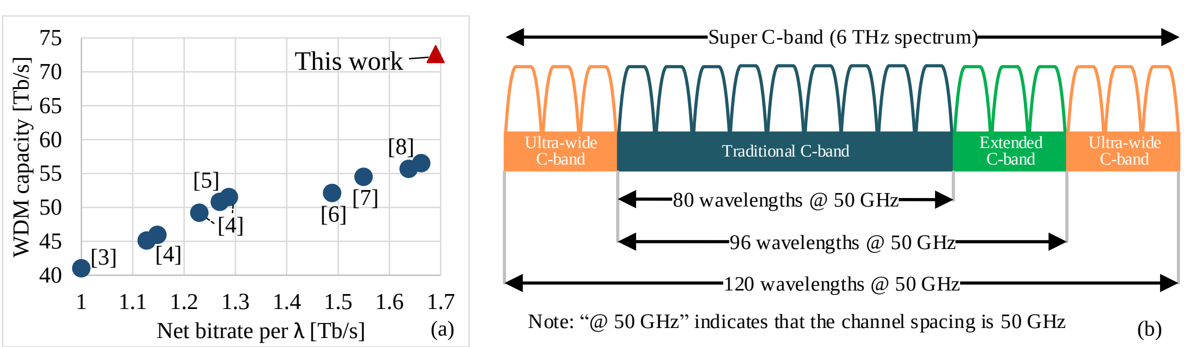

Fig. 1. Reported DWDM capacity vs per-carrier net bitrate exceeding 1 Tb/s/λ (a). Super C-band representation (b).

2. Transmission Setup

The transmission setup, shown in Fig. 2, is similar to the one used in [8]. The data signal consisting of four real components is generated by a Keysight M8199A arbitrary waveform generator (AWG) having a 3 dB-bandwidth of 55 GHz, effective number of bits (ENOB) of at least 5 bits all over the bandwidth, and a sampling rate of up to 128 GSa/s [14]. As in [8] we have increased the sampling rate of the AWG to 130 GSa/s. The electrical outputs of the AWG are connected to four SHF M827B single-ended RF amplifiers with 72 GHz 3 dB-bandwidth and 11 dB gain driving two electro-optic Axenic aXSD2050 GaAs IQ modulators having 6 dB-bandwidth exceeding 50 GHz and 4.5 V $V\pi$. [10]. The output of a Keysight 81606A tunable external cavity laser (ECL) with <100 kHz linewidth is split in a polarization maintaining (PM) splitter and amplified by two Amonics PM EDFAs before feeding the two IQ modulators (IQMs) with 18 dBm optical power. The dual-polarization (DP) signal is obtained by recombining the output of the IQMs using a polarization beam combiner (PBC). The DP signal is amplified by an EDFA before applying 8 dB linear pre-emphasis to flatten the power spectral density of the modulated signal by means of a II-VI waveshaper 4000B/X. This waveshaper is based on Liquid Crystal on Silicon (LCoS) technology allowing arbitrary optical filter attenuation and phase across the entire C+L band (185.86 THz to 196.672 THz). The waveshaper provides a high-resolution mode of operation in which the optical signal passes twice through the grating based monochromator. It enables the application of the optical pre-emphasis on the channel under test and the generation of the neighboring DWDM channels with an ASE bandwidth loading method [11] assuming a 137.5 GHz channel spacing. The 43 channels are generated with center frequency between 190.8 THz and 196.58 THz. The booster EDFA is operated to deliver its maximum output power of 22.5 dBm. The DWDM spectrum is transmitted with 2 dB tilt, as shown in Fig. 2(a), optimized to achieve a flat DWDM spectral profile and best average per-channel performance after the receiver EDFA. The optical link consists of 100 km of Sumitomo "Z-Plus fiber 130" compliant with ITU-T G.652.D. This pure-silica core fiber having ultra-low attenuations as low as 0.152 dB/km and enlarged effective core area allows realizing high-SE digital coherent DCI systems. Another EDFA is used before the demux performed by using a Yenista XTA-50 tunable bandpass filter set to 137.5 GHz followed by an additional EDFA, which keeps the optical power at the input of the receiver at 7 dBm. The super C-band EDFAs employed in this experiment exhibit noise figure <5.5 dB at the best operating point and cover a frequency range between 190.68 THz to 196.68 THz (Fig. 2(b)) with tunable gain ranging from 8 dB up to 32 dB. As represented in Fig. 1(b), the super C-band includes the ultra-wide C bands (1.2 THz) in addition to the traditional C-band (4 THz) and the extended C-band (0.8 THz). It increases the number of available channels and maximizes the fiber capacity with a single line system [9].

The receiver consists of a coherent mixer and four Finisar 100 GHz balanced photodetectors (BPDs), with 0.45A/W responsivity, connected to a 256 GSa/s Keysight UXR oscilloscope with 80 GHz bandwidth. Another Keysight 81606A ECL followed by an Amonics PM-EDFA is used as local oscillator achieving 18 dBm optical power.

The receiver digital signal processing (DSP) makes use of advanced and fully adaptive nonlinear component equalizers, targeting imperfections such as bandwidth limitations, frequency dependent I/Q imbalance and skew, phase ripple, I/Q crosstalk and high-order nonlinearities at transmitter and receiver. At the receiver, a first digital Volterra equalizer (Rx-NLE in Fig. 2) addresses the imperfections of the receiver components, i.e. optical-electronic frontend and analog-to-digital converter (ADC). After channel equalization and demodulation (including carrier phase recovery), another Volterra equalizer (Tx-NLE in Fig. 2) compensates for the residual imperfections of the transmitter. The nonlinear equalizers operate on the real tributaries rather than on the complex baseband signals. To compensate for the crosstalk among the tributaries, which might arise e.g. due to the finite extinction ratio of the IQ modulator, we implemented the Tx-NLE using a real 4×4 MIMO structure. Finally, partial-response equalization (PREQ) with impulse response $1 + \alpha D$ is implemented to whiten the noise, followed by a complex-valued BCJR algorithm with one memory tap used for maximum a posteriori (MAP) symbol detection.

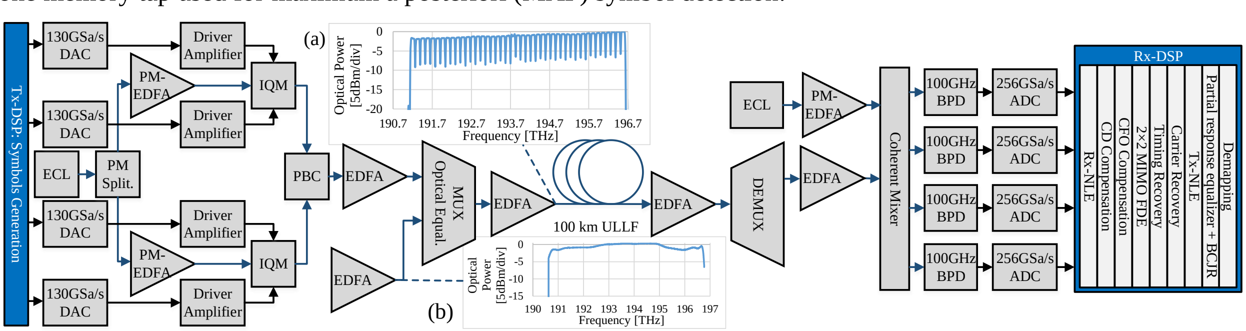

Fig. 2. Schematic of the experimental setup, insets: 43-channel DWDM transmitted spectrum (a) and super C-band EDFA gain spectrum (b).

3. Experimental Results over Field-Deployed Fiber

Measurements are performed using a family of PCS256QAM formats of variable entropy (H) assuming a probabilistic amplitude shaping (PAS) [12] architecture. As shown in Fig. 3(a), we varied the alphabet entropy using Maxwell-Boltzmann distributions from 7.1 bits/symbol/pol to 8 bits/symbol/pol based on the channel with central frequency at 191.625 THz. Considering a known family of forward-error correction (FEC) codes [13] the highest net bitrate was obtained at 7.7 bits/symbol/pol. The same optimum entropy was obtained sweeping the entropy over higher frequencies channels. The Rx-NLE is set to have 700 linear taps and 3 taps of the 2nd order, the Tx-NLE is set to have 2000 linear taps, 19 taps of the 2nd order, 11 taps of the 3rd order and 7 taps of the 5th order. The large number of linear taps in the equalizers is chosen to cope with reflections inside sub-components (e.g. the IQ modulator) and in the setup assembly. The number of coefficients of the equalizers could be reduced with negligible impact on performance in an integrated device. The nonlinear distortions in the setup mainly come from DAC, drivers and IQM. As reference, for the electrical back-to-back case the signal-to-noise ratio (SNR) after linear equalization exceeds 25 dB. The AWG output amplitude was tuned depending on the modulation format and entropy from 470 mVpp (H=8 bits/symbol/pol) to 770 mVpp (H=7.1 bits/symbol/pol) to keep the optical average power after the IQM constant.

As shown in Fig. 3(b), the average per-carrier net bitrate of the 43 channels DWDM system is 1.69 Tb/s leading to a total DWDM capacity of 72.64 Tb/s with SE=12.29 bits/s/Hz. In Table 1, we display the three FEC overheads considered in the DWDM experiment, as well as their BER and NGMI [14] thresholds [13]. For each DWDM channel, we choose the lowest FEC overhead for which both BER and NGMI requirement are fulfilled. Following [15], we then calculate the accumulated net bitrate: $AccNetBitRate = 2 \cdot (\sum_{i=1}^{43} H - 8 \cdot (1 - R_{fec}^{i}))$, where R_{fec}^{i} is the FEC rate selected for the DWDM channel i.

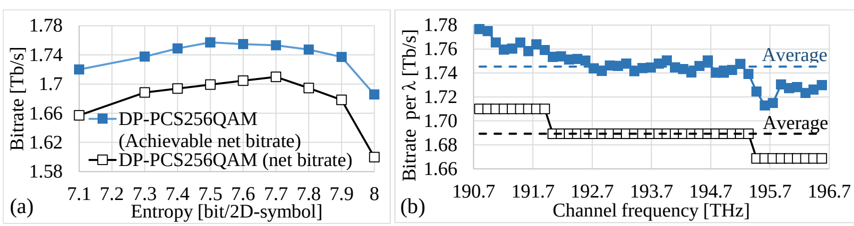

Fig. 3. Bitrate vs entropy (a), bitrate per DWDM channel (b).

Table 1. Key parameters of the FEC codes considered in the DWDM experiment.

FEC Overhead	R_{fec}	Required BER	Required NGMI
19.089%	0.84	3.96E-02	0.8551
17.698%	0.85	3.58E-02	0.8680
16.339%	0.86	3.38E-02	0.8751

4. Conclusions

We have reported a capacity record of 72.64 Tb/s over a single optical line system using a 43-channel DWDM configuration over a 100 km ultra-low loss fiber. With respect to the previous record, we have increased the DWDM capacity by 28.5% extending the usable spectrum around the C-band by 17.6% and increasing the spectral efficiency by 8.9% achieving 12.29 bits/s/Hz by means of advanced nonlinear DSP.

5. References

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