Record 300 Gb/s per Channel 99 GBd PDM-QPSK Full C-Band Transmission over 20570 km Using CMOS DACs

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Abstract: We demonstrate a record 300 Gb/s per-channel bitrate over 20570 km across the full C-band. The measured 41 channels are modulated with 99 GBd PDM-QPSK using CMOS DACs and optical pre-emphasis, avoiding nonlinear compensation.
OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

1. Introduction

Thanks to the sustained interest in the submarine optical transport systems to develop the infrastructure for telecommunications operators and web-scale players around the globe, the industry is thriving, and new paradigms for system architecture are emerging since 2017. Given the main criterion is the total cost per bit, and that the delivered electrical power in submarine systems is limited by the power feeding equipment technology, the current trend in submarine systems is not anymore maximizing the per-fiber capacity by applying nonlinear compensation (NLC) to increase the spectral efficiency as much as possible (as e.g. in [1-3]), but instead, backing off on the launched power, avoiding power-hungry NLC, and adding more submerged fiber strands, together with pump farming [4-7]. The cost concerns also favor migrating towards ever increasing per-channel symbol-rates, hence reducing the transponder count [8-10]. Moreover, to be flexible in overall optimization of their network, some customers are now interested in submerged cables reaching out 17000 km or more. These new requirements motivated us to recently conduct a 98 GBd PDM-QPSK transmission experiment over 17545 km of EX3000 fiber, by measuring the performance of a single channel in the middle of C-band, using cutting-edge CMOS technology for transmitter, together with electrical and optical pre-emphasis assuming decoding with commercial forward error correction (FEC) [10]. In this paper, we extend our previous work by increasing the distance to 20570 km and measuring the performance of all the 41 channels, 100 GHz spaced across the full C-band. The channels are modulated with 99 GBd PDM-QPSK and decoded with high performance adaptive-rate spatially-coupled low-density parity check (SC-LDPC) codes with variable rates adapted to the channel signal-to-noise ratio (SNR) [11,12]. We demonstrate that all channels can be successfully decoded with the FEC rate of 0.77 at the nonlinear threshold (NLT), without using NLC, thus achieving a record net 301.87 Gb/s per channel for all the 41 channels. Moreover, we also measure all the channels down to NLT – 3dB and examine the transmission power efficiency evolution when reducing the total launched power in the fiber.

2. Experimental setup

Our experimental setup is depicted in Fig. 1. The transmitter is made of 82 loading channels in C-band in a 50 GHz grid and a test group of three 100 GHz-spaced adjacent channels. We use three tunable laser sources (TLS) for the test group, and the central channel under test (CUT) is modulated with a dual polarization in phase and quadrature (DP-I/Q) Lithium Niobate modulator driven by a CMOS DAC operating at 118 GSa/s and loaded with 99 GBd PDM QPSK randomly generated sequences. In order to compensate for the limited electro-optical bandwidth, the signal is optically shaped over a 100 GHz bandwidth using a commercially available 6.25 GHz-grid-resolution wavelength selective switch (WSS) [9]. Two other TLS are modulated by a distinct CMOS DAC fed with different sequences, to create two adjacent 99 GBd channels. Like the CUT, a WSS is used to optically shape the adjacent channels. For the three channels of the test group, electronic predistortion is applied together with optical spectrum shaping. The ratio between optical and electrical frequency pre-distortion is fine-tuned to minimize the back-to-back penalty as described in [9]. The loading channels are separately modulated with a DP I/Q modulator operating at 88 GSa/s and fed with 49 GBd QPSK sequences. After amplification, a 50 GHz-grid-resolution WSS is used to equalize the WDM spectrum over the C-band and reject the loading signal in the corresponding 300 GHz slot of the test group. A 50 km fiber spool and a polarization scrambler (PS) ensures decorrelation and a variable random state of polarization of the loading signal

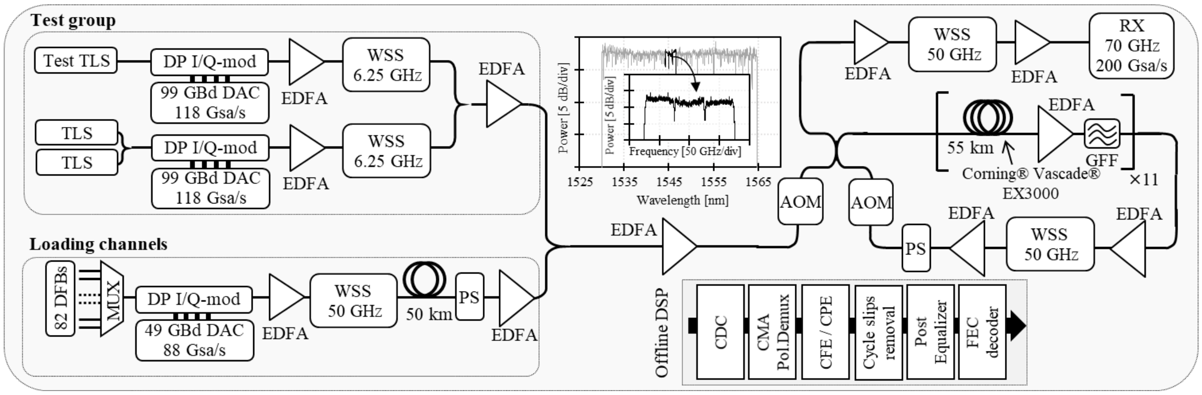

Fig. 1: Experimental setup (TLS: tunable laser source, DFB: distributed feedback laser, DAC: digital-to-analog convertor, DP I/Q-mod: dual polarization in phase and quadrature modulator, WSS: wavelength selective switch, PS: polarization scrambler, EDFA: Erbium-doped fiber amplifier, AOM: acousto-optic modulator, DSP: digital signal processing, GFF: gain flattening filter, CDC: chromatic dispersion compensation, CMA: constant modulus algorithm, CFE: carrier frequency estimation, CPE: carrier phase estimation, FEC: forward error correction)

before coupling to the test group. The WDM signal is then amplified by a last EDFA before being sent into the recirculating loop. The central inset of Fig. 1 shows the full C-band spectrum (grey line), with the 300 GHz wide test group depicted in black line and composed of our three adjacent 99 GBd PDM-QPSK channels.

The transmission loop is made of 11 spans of 55 km EX3000 fiber followed by EDFAs with output power ranging from 15 to 18 dBm. A gain flattening filter (GFF) is used after each EDFA to equalize the power profile over the C-band. At the output of the 11 spans, we use a 50 GHz-grid-resolution WSS for channel power equalization. A loop-synchronous PS is used to randomly rotate the state of polarization after each recirculation in the loop. At the receiver (RX), the CUT is extracted using a WSS, amplified and sent to the coherent receiver. Electrical waveforms are sampled with a 70 GHz bandwidth high speed sampling scope operating at 200 GSa/s. Data sets of 2 million samples are stored and offline digital signal processing (DSP) is performed. After electronic chromatic dispersion compensation (CDC), polarization demultiplexing is performed by blind constant modulus algorithm (CMA), followed by carrier frequency and phase estimation (CFE/CPE). Cycle slips are detected and removed with the help of 1% pilot symbols inserted in the sequences. A least-mean square symbol-spaced blind equalization is used before SNR estimation. Processed signals are decoded using a family of SC-LDPC codes [11] with rates ranging from 0.4 to 0.91, using steps of 0.01. For each file we decoded the received waveforms by using family members selected through bisection search and we determined the maximum code rate resulting in error-free transmission [12].

3. Transmission results

We first show in Fig. 2a the numerical back-to-back FEC characterization (circle markers). For each value of the SNR, with resolution of 0.25 dB, the graph indicates the maximum rate of our FEC decoding while examining all members of our SC-LDPC code family. With a SNR equal to 4.5 dB, the maximum achievable code rate is 0.77, corresponding to a net 301.87 Gb/s bit rate (assuming 1% pilot symbols). The solid line stands for the normalized generalized mutual information (GMI) calculated as 0.5×GMI/pol (the factor 0.5 corresponds to the number of 2 bits per symbol per polarization for the QPSK signal) and represents the rate for an ideal FEC decoder. Fig. 2b shows the measured SNR (circle markers, left axis) of all 41 channels in the C-band when sweeping the test group over the whole C-band, after 20570 km (i.e. 34 re-circulations in the loop) and for a launched power per span of 18 dBm, corresponding to the NLT

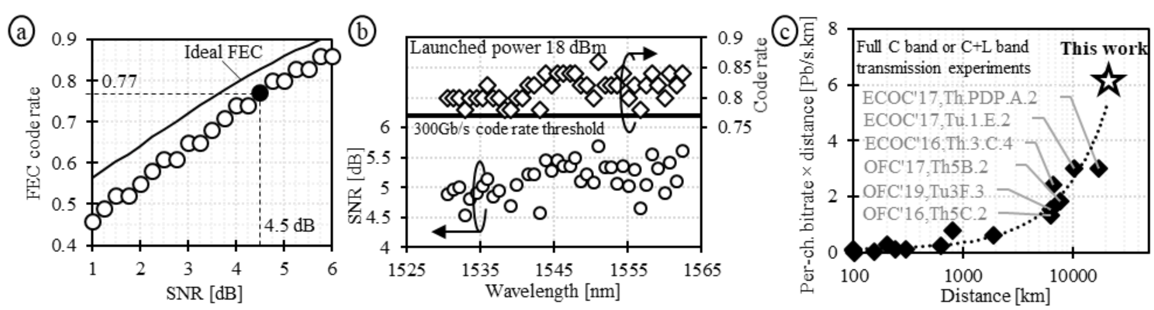

Fig. 2: a) Back-to-back characterization of FEC decoder family, b) measured SNR and maximum code rate of the 41 C-band channels after 20570 km, and c) evolution of per-channel bit rate times distance product in transoceanic capacity record experiments

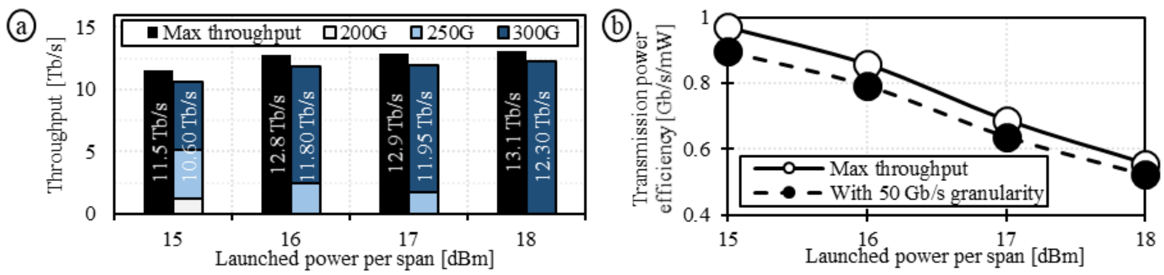

Fig. 3: a) maximum achievable throughput and b) transmission power efficiency versus launched power per span after 20570 km

[10]. The measured SNR after DSP ranges from 4.54 to 5.7 dB and we apply our SC-LDPC FEC decoders to all channels and determine the highest rate resulting in error-free transmission for each of them. Diamond markers in fig. 2b depicts these maximum code rates, ranging from 0.78 to 0.86 across the C-band. As all code rates are above the 0.77 code rate threshold, all our transmitted channels can transport a net bit rate of 301.87 Gb/s. Fig. 2c compares our result with previous transoceanic capacity record experiments.

We then reduced the amplifier output power by steps of 1 dBm. The performance of all channels was measured for each launch power setting and Fig. 3a shows the maximum achievable throughput for each configuration (black bars). With a launched power per span of 18 dBm, the total throughput reaches 13.1 Tb/s. While 18 dBm corresponds to the NLT in this loop [10], we show that decreasing the total power down to 16 dBm implies a very small decrease (< 3%) of the total throughput. Further decreasing the launch power to 15 dBm results in a higher reduction of the total throughput down to 11.5 Tb/s, corresponding to 12%, which is attributed to the fact that we enter the linear regime of fiber propagation. We also determined the transmission throughput when considering practical 50 Gb/s granularity of client interfaces. In Fig. 3a we represent the breakdown of the 41 C-band channels between 300G channels (dark blue, right columns), 250G channels (light blue, right columns) and 200G channels (white, right columns). All channels transport 300G when the launched power is 18 dBm, and the total throughput is 12.30 Tb/s. When the power is decreased to 17 dBm, 7 channels out of 41 must be downgraded to 250G and the net throughput decreases to 11.95 Tb/s, corresponding to a 3% reduction of the capacity. With a total power of 15 dBm, a few channels are downgraded to 200 G and we obtain a total throughput of 10.60 Tb/s, corresponding to a reduction of 14% compared to the optimal power of 18 dBm. Fig. 3b shows the evolution of the transmission power efficiency, defined as the ratio of the total throughput to the total integrated launched power, as a function of the launched power per span. This figure clearly reflects the attraction of the current trend in the submarine industry towards spatial division multiplexing. Considering 50 Gb/s granularity, reducing the total throughput by 14% while dividing the launched power by two leads to increasing the transmission power efficiency from 0.52 Gb/s/mW to 0.90 Gb/s/mW.

4. Conclusions

We demonstrate a record per-channel net 300 Gb/s for 41 WDM channels, 100 GHz spaced across the full C-band, over 20570 km using EDFA-only amplification and avoiding nonlinear compensation. We also show that operating the system at the launched power of 3 dB below the nonlinear threshold enables increasing the transmission power efficiency from 0.52 Gb/s/mW to 0.90 Gb/s/mW. Our demonstration is compatible with the current practical industrial paradigm of favouring the cost-per bit per cable as the main metric in power-constrained subsea systems.

5. References

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