65Tb/s Transoceanic Transmission Using Probabilistically-Shaped PDM-64QAM

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Abstract *We report on a C+L-band transoceanic transmission using capacity-approaching probabilistically-shaped 64QAM. Digital nonlinear compensation and adaptive-rate spatially-coupled LDPC decoding enable transmission of 65 Tb/s over 6600km, with spectral efficiency of 7.3 b/s/Hz.*

Introduction

A variety of techniques has been proposed to increase the throughput of submarine coherent polarization-division multiplexed (PDM) transmission systems[1-4]. Recent studies focused on capacity-achieving constellations together with low-complexity bit-interleaved coded modulation (BICM) to avoid complex iterative decoding. Using 24.5 GBd 64APSK, digital nonlinear compensation (NLC) and quasi-single mode fibers a spectral efficiency (SE) beyond 8 b/s/Hz was reported over C-band[4]. Submarine systems may rely on dual C- and L-band amplification to further increase net throughput per cable. Fiber stimulated Raman scattering penalizes C+L-band transmission with respect to C-band transmission. The most reliable amplification scheme from industrial viewpoint is based on erbium doped fiber amplifiers (EDFA) for both bands. Dual C+L-band EDFA amplification scheme induces further constraints on signal-to-noise ratio (SNR) due to C/L-band multiplexing and demultiplexing insertion loss. The highest SE reported so far for C+L-band transoceanic transmission systems is 6.9 b/s/Hz. Using 32.4 GBd single parity check 64QAM (SPC-64QAM) coded modulation and adaptive-rate iterative decoding, that experiment demonstrated a total capacity of 61.9Tb/s over 5920 km[3], but with hybrid Raman-EDFA continuous-band amplification.

In this paper we use the capacity approaching probabilistically shaped 64QAM[5,6] (PS64QAM) to demonstrate a full C+L-band transoceanic transmission with dual-band EDFA amplification. The main building block of the PS64QAM proposed in[6] is a programmable distribution matcher that controls source entropy by applying fixed length coding at the bit-to-symbol mapping level allowing tailoring the source entropy to the SNR region of interest by suitably choosing the probability mass function (PMF) of the constellation points. Fig.1a illustrates the theoretical generalized mutual information (GMI) of the PS64QAM format designed for this work and Shannon capacity. GMI is the appropriate metric for analyzing system performance with BICM. The gap to capacity was minimized (< 0.1 dB) over the SNR interval from 10 to 12.5 dB corresponding to the end-link SNRs in our experiment. Fig. 1b shows the PMF of the designed PS64QAM over the in-phase signal levels. The PMF of quadrature levels is identical to that of in-phase levels. Fig. 1c shows that this design outperforms 64APSK[4], SPC-64QAM[3], 16-, 32- and 64QAM assuming BICM.

In this work, we adopt the high symbol rate of 49 GBd in order to reflect industry's trends towards reducing cost per bit, and report on the first C+L-band transoceanic transmission achieving 65 Tb/s over 6600 km with dual-band EDFA amplification, using PDM-PS64QAM, NLC and adaptive-rate BICM decoding.

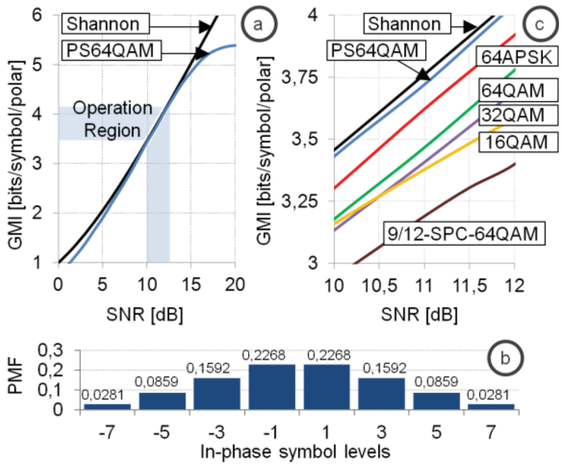

Fig. 1: a) the generalized mutual information (GMI) of the custom designed PS64QAM, tailored to our experiment, b) the probability mass function (PMF) of the in-phase levels, c) a comparison of the GMI of various modulation formats.

Setup

Fig. 2a illustrates the C-band transmitter setup (TX C). The test channel was a single tuneable laser source (TLS) modulated with a

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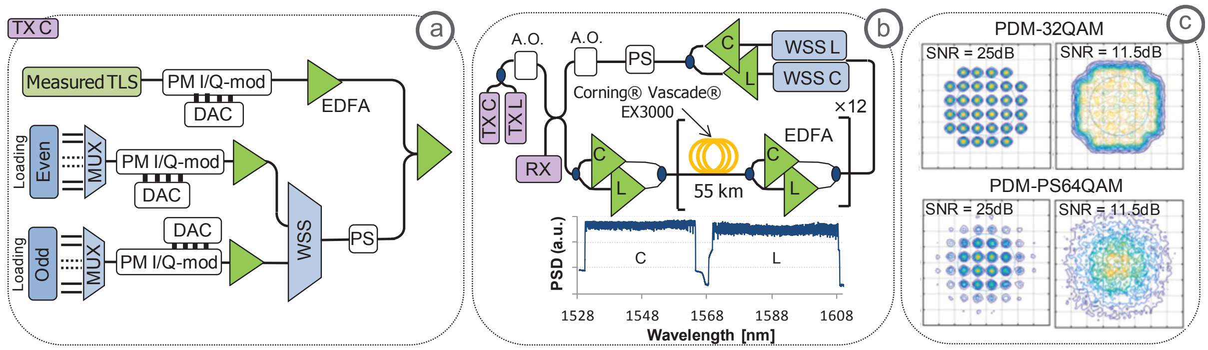

Fig. 2: a) C-band transmitter, b) the recirculation loop, inset: total spectrum at loop injection point c) experimental constellations TLS: tunable laser source, DAC: digital-to-analog convertor, WSS: wavelength selective switch, PS: polarization scrambler.

polarization-multiplexed I/Q modulator (PM I/Q-mod), surrounded by 87 loading channels, divided into even and odd rails, modulated with distinct modulators. Each modulator was driven by a dedicated digital-to-analogue convertor (DAC) loaded with different randomly-generated sequences operating at 88 Gsamples/s. The sequence length was 36492 symbols. Pulse shaping was performed using root-raised cosine pulses with roll-off 0.01. Loading channels were coupled through a wavelength selective switch (WSS) to the measured channel. a polarization scrambler (PS) were placed at WSS output. The L-band transmitter (TX L) was similar to TX C, consisting of one test channel plus 90 loading channels, leading to a total number of 179 C+L channels. Fig. 2b shows the recirculation loop. The loop was composed of twelve 55 km spans of Corning Vascade EX3000 low-loss fiber, with 0.157 dB/km loss. The average span loss, including fiber, C/L-demultiplexer, connectors and splicing loss was 10.2 dB. The loop included a gain equalizer WSS per band and a loop synchronous polarization scrambler.

The transmitted signal was received after 10 loops, by a real-time scope with 33 GHz bandwidth, sampling at 80 Gsamples/s. Signal processing consisted of chromatic dispersion compensation, followed by polarization de-multiplexing. While constant-modulus algorithm (CMA) can successfully demultiplex unshaped QAM signals, the PS64QAM was processed with a 1% pilot-assisted multi-modulus algorithm (MMA) after pre-convergence by CMA. Then carrier frequency and phase recovery using blind phase search, pilot-based cycle-slip removal using 1% pilots and least-mean square adaptive post-equalization were applied before computing SNR and GMI (corrected for pilot overheads) and applying multi-rate spatially coupled LDPC (SC-LDPC) FEC decoding[8, 2].

Results

In this work, we compare the performance of our custom PS64QAM with 10.8 bits/symbol and that of 32QAM with 10 bits/symbol. The highest reported C-band throughput (33 Tb/s) over the longest distance (6800 km) up now is made using 32QAM[4]. System performance was studied in terms of both SNR and GMI. SNR is the conventional physical measure of transmission, for which analytical expressions exist even in the nonlinear regime[10], whereas GMI is the direct measure of the net transmitted information. On the other hand the pre-FEC bit error ratio (or the quality factor) are not suitable for comparing modulation formats with different spectral efficiencies, and do not convey new information once the GMI is computed, and therefore are not used in this work. In order to theoretically estimate the nonlinear SNR, the perturbative model[9] was adapted by computing the fourth and sixth constellation moments for PS64QAM and 32QAM. Fig. 3a illustrates the experimental (markers) and theoretical (lines) SNR and GMI as a function of the total launched power. Measurements are performed at 1550.51 nm. The total launched power was swept from 19 to 23 dBm. In terms of nonlinear tolerance PS64QAM is inferior to 32QAM as shown by its lower SNR at optimum launched power; however, PS64QAM preserves its superior performance over 32QAM in terms of GMI even in the nonlinear regime.

Based on the results of Fig. 3a, the total launched power was set to 22 dBm and all channels were measured with PDM-PS64QAM format. The recorded waveforms of all channels were processed with and without NLC. The NLC algorithm used in this work was digital backpropagation (DBP). Fig. 3b shows the measured SNR and GMI values without NLC (filled markers) and with NLC (empty markers) using DBP. Due to experimental uncertainties, the power of each channel is not exactly equal to the required optimum launched power. In order to maximize the performance improvement offered by NLC, the DBP was adapted on a channel-by-channel basis by

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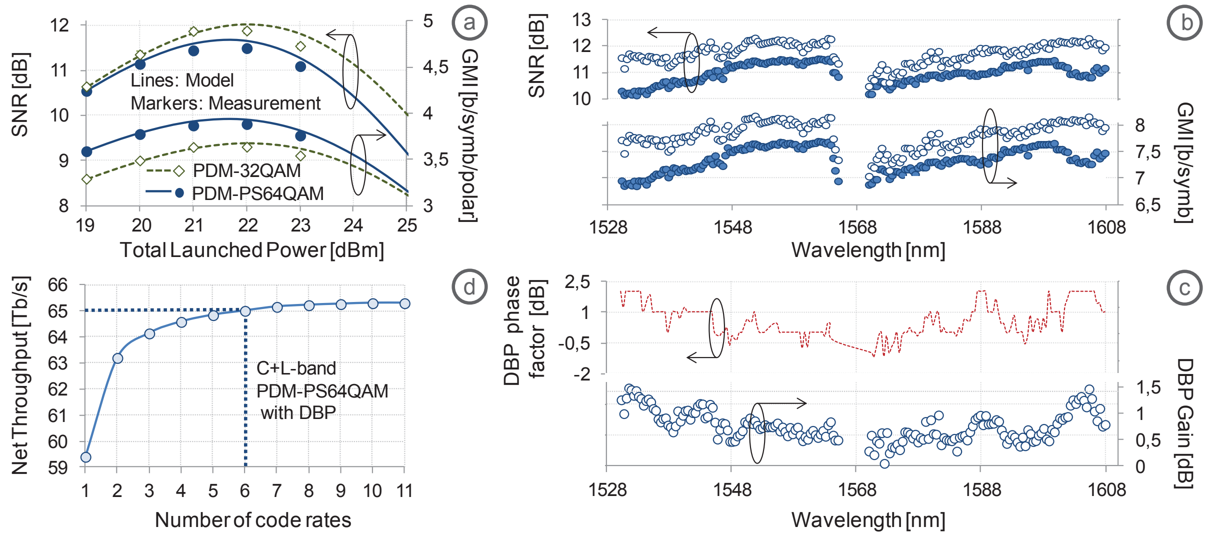

Fig. 3: a) comparison of the nonlinear performance of PS64QAM and 32QAM without nonlinear compensation (NLC), b) Measured GMI and SNR of PS64QAM with and without NLC, c) DBP SNR gain, and DBP optimized phase factor, for PS64QAM d) Net throughput vs. number of optimized code-rates for nonlinearly compensated PS64QAM.

optimizing the nonlinear phase factor (cf. Eq. (1-b) in[8] and (1-3) in[2]) per wavelength. Fig. 4c shows the optimized phase factor in dashed red line and the DBP SNR gain across the whole band in blue circles. Channels that operate more deeply in the nonlinear regime, *e.g.*, at the left C-band edge, require higher nonlinear phase factor, and consequently enjoy from more improvement after post-compensation by DBP.

Finally, all nonlinearly compensated PS64QAM channels were decoded using 26 members of the family of SC-LDPC[1,2,8] codes with rates between 0.66 and 0.91. For any number of allowed code rates between 1 and 26, we used the trellis-based dynamic programming rate optimization algorithm[2] to choose the rates that maximize the total net throughput. Fig. 4d shows the total net throughput versus number of optimized codes rates. Using a single code rate, the net throughput is 59.4 Tb/s, which is equivalent to 331.83 Gbits/s per channel. With six optimized code-rates, the total net throughput reaches 65 Tb/s, which is equivalent to average 363.10 Gbits/s. The maximum net throughput of 65.29 Tb/s is achieved with 10 optimized code-rates. Fig. 4 puts our result in perspective with respect to previous record transoceanic C+L records

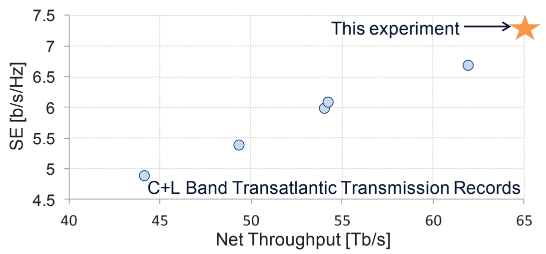

Fig. 4: Recent transoceanic C+L transmission records.

Conclusions

We reported on a C+L-band EDFA-only transoceanic transmission using 179 channels of 49 GBd probabilistically-shaped 64QAM. Thanks to the custom designed probablistically shaped 64QAM format, channel-adaptive nonlinear compensation and six optimized code rates of spatially-coupled LDPC FEC decoders, we demonstrated 65 Tb/s over 6600 km, achieving a spectral efficiency of 7.3 b/s/Hz.

Acknowledgements

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