POWER EFFICIENT TRANSMISSION OF 320 GB/S OVER 17545 KM, AND 560 GB/S OVER 6050 KM USING 98 GBd QPSK AND 64QAM AND CMOS TECHNOLOGY

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Abstract

We demonstrate power efficient 320 Gb/s transmission over 17,545 km, and 560 Gb/s over 6,050 km, using 98 GBd PDM-QPSK/64QAM and CMOS DAC technology, while applying digital and optical pre-emphasis. At the receiver side the standard digital signal processing is employed. nonlinear compensation was avoided.

1 Introduction

Motivated by the recent increasing webscale demand for transoceanic traffic volume, in the past two years a paradigm shift in the design of submarine fiber-optic transmission systems has taken place: the key criterion is no more maximization of the net throughput per fiber strand by maximizing the spectral efficiency, instead, the net throughput per a multi-strand submarine cable is to be maximized under the constraint of fixing the total power consumption. This evolution is known as SDM technology [1], consisting of increasing the number of fiber pairs from 4 up to 16 and beyond, and operating the WDM channels below the nonlinear threshold (NLT), thus the use of nonlinear compensation is ruled out [2]. To further reduce the cost per-bit, it is desirable to increase the per-channel symbol-rate, hence decreasing the number of transceivers per fiber strand. Note that, although subcarrier multiplexing might provide some resilience to nonlinear impairments, especially for QPSK format [3], if operated below NLT, this improved resilience to nonlinear impairments becomes irrelevant. Since 2014, a few research groups have proposed solutions based on geometric and/or probabilistic constellation shaping, and digital nonlinear compensation and demonstrated record per-strand spectral efficiencies and total throughputs across the C+L band up to 2017 [4-6]. In the new paradigm the simple signal processing operating at high baud-rate in the linear regime across C band is favoured, in order to curb the cost per bit and sustain system scalability proportional to the increasing submarine traffic demand. In this paper, for the first time we demonstrate transoceanic transmission of 98 GBd polarization division multiplexed (PDM) QPSK channels over extremely long transpacific 17,545 km, and 64QAM channels over transatlantic 6,050 km, using cutting edge digital-to-analog converters operating at 118 GSamples/s. Contrary to [7] and [8] relying on BiCMOS technology, we use here CMOS technology for digital-to-analog convertors (DAC), and operate at the lower symbol-rate of 98 GBd to fit to the 100 GHz spacing grid.

2 Experimental setup

Fig. 1a demonstrates the experimental setup. The transmitter signal was a WDM comb composed of 86 C-band DFB lasers spaced at 50 GHz. These dummy channels were modulated with 49 GBd PDM QPSK/64QAM signals generated by DACs operating at 88 Gsamples/s. The test channel was a TLS laser with linewidth less than 30 kHz, modulated with a 98 GBd signal (either PDM-QPSK, or PDM-64QAM), generated by a CMOS DAC operating at 118 Gsamples/s. Random sequences of 54428 symbols were used for each polarization on the test channel. Dummy channels were modulated with different sequences. Standard $LiNbO_3$ IQ-modulators (IQ-mod) were employed. A standard 6.25 GHz-grid-resolution wavelength selective switch (WSS), the WSS1, was placed at the output of the test channel IQ-modulator to linearly equalize the wideband test channel in the optical domain. As demonstrated in [9], the optimum frequency pre-compensation for wideband signals is achieved by doing both digital, and optical equalization, to avoid sacrificing the limited ENOB of the DAC. Fig. 1b illustrates the spectral mask for digital pre-compensation, whereas Fig. 1c shows the pre-emphasis profile programmed into WSS1. We inserted erbium doped fiber amplifiers (EDFA)s before and after WSS1 to compensate for the insertion loss of IQ-mod and WSS1. Fig. 1d illustrates the optical spectra at the transmitter output, without and with frequency pre-compensation. The pre-compensation masks were iteratively fine-tuned to maximize the electrical SNR. The dummy channels were modulated by separate random sequences. The dummy comb passed through a polarization scrambler (PS) before being multiplexed with the test channel. The 50 GHz-grid-resolution WSS2 was programmed as a 100 GHz stopband notch filter across the test channel spectrum and used

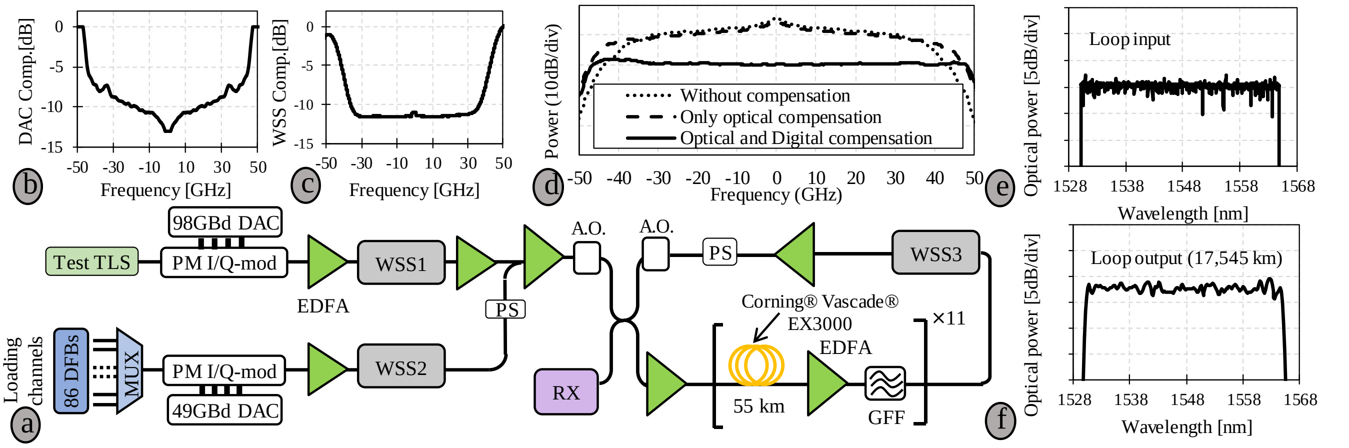

Fig. 1. (a) : experimental setup: TLS: tuneable laser source, DFB: distributed feedback laser, DAC: digital-to-analog convertor, WSS: wavelength selective switch, PM I/Q-mod: polarization-multiplexed IQ modulator, A.O.: acousto-optic switch, PS: polarization scrambler, EDFA: erbium-doped fiber amplifier; (b) spectral mask for digital pre-compensation by the DACs, (c): spectral mask for optical pre-compensation by WSS1, (d) channel spectrum at transmitter output, (e) WDM spectrum at the input of the recirculation loop, (f) WDM spectrum at the recirculation loop output.

to flatten the power profile otherwise. The test channel and the dummy WDM comb were multiplexed together and launched into the recirculation loop. This loop consisted of 11 spans of 55 km Corning EX3000 fibers, with 0.157 dB/km loss coefficient, 20.5 ps/nm/km dispersion coefficient at 1550 nm, and 150 µm^2 effective area. The span loss was compensated at the end of each span by a C-band EDFA followed by a gain flattening filter (GFF). The 50 GHz-grid-resolution WSS3 was placed after the last span of the loop to equalize WDM channels across the whole C-band. A loop synchronous polarization scrambler was placed after the equalizer WSS3, to decorrelate the relative state of polarization of WDM channels. Each loop thus emulated transmission over 605 km. We then performed transmission experiments at three wavelengths after 10 loops (6,050 km) using 98 GBd PDM-64QAM, or at a single wavelength after 29 loops (17,545 km) using 98 GBd-PDM QPSK signals. The picked-up signal at the loop output was received by a standard coherent receiver front-end and sampled at 200 Gsamples/s using a 70 GHz real-time sampling scope. The offline DSP was applied to the recorded sampled waveforms. The standard DSP suite, including chromatic dispersion compensation, complex MIMO 2x2 constant modulus algorithm, FFT-based frequency offset, and blind phase search carrier phase recovery (with 2% pilot overhead to remove cycle-slips), followed by LMS equalizer. The LMS equalizer had 101 taps to efficiently mitigate inter-symbol interference (ISI) of the wideband channel. Then, the signal-to-noise ratio (SNR) of the received signals was calculated and the post-FEC net bit rate and achievable bit rates were computed.

3 Results

Fig. 2 shows the SNR vs. OSNR back-to-back curves for 49 GBd (for reference) and 98 GBd PDM-QPSK and PDM 64QAM signals at 1542.34 nm. The SNR is averaged over the two polarizations and the SNR difference between the two

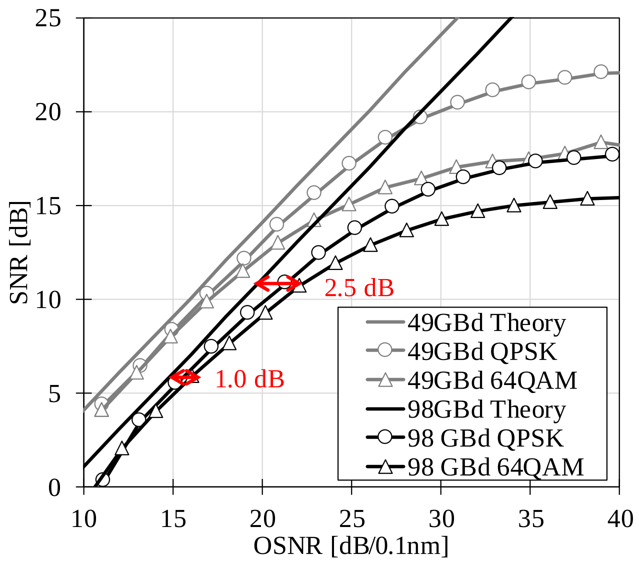

Fig. 2. Back-to-back performance.

polarizations was less than 0.3 dB in all cases. At the target SNR of 5.9 dB for PDM-QPSK (cf. Fig. 3c), the penalty with respect to theory of 49 GBd is less than 0.5 dB. For the 98 GBd PDM QPSK signal this penalty rises to about 1 dB. The SNR ceiling of 49 GBd PDM QPSK signal is 22 dB, and it is reduced to 17 dB for the 98 GBd signal. At the target SNR of 10.5 dB for 64QAM, the penalty with respect to theory is 0.6 dB for 49 GBd 64QAM signals, and it increases to 2.5 dB for the 98 GBd 64QAM signal. The SNR ceiling for 49GBd 64QAM signal is 17 dB, and it reduces to 15 dB at 98 GBd.
After the back-to-back characterizations, we conducted transmission experiments over transatlantic, and transpacific distances. First, we report on transatlantic measurements. Fig.3a shows the SNR vs. total launched power bell curves for 98 GBd PDM-64QAM measured after 10 loops, *i.e.*, 6,050 km. We measured three different wavelengths across the C-band.

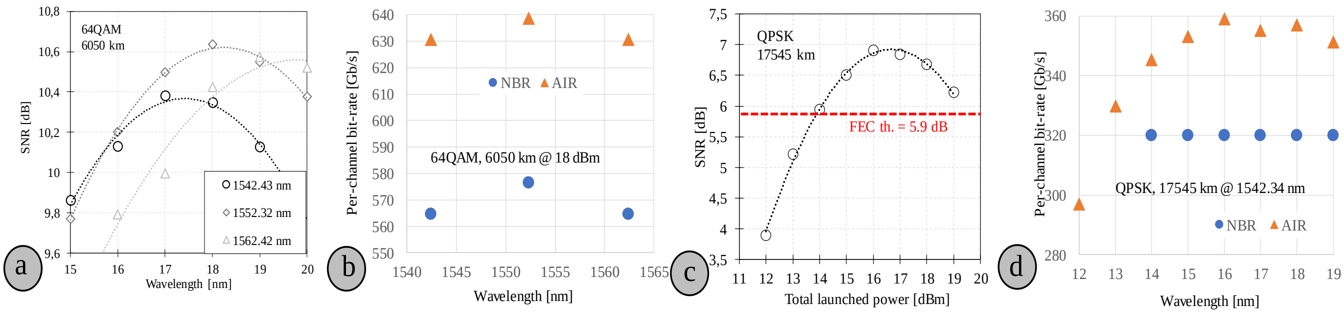

Fig. 3: Transmission results: (a) and (b) 64QAM for transatlantic, (c) and (d) QPSK for transpacific.

The powers of WDM channels were varied altogether to sweep the total launched power. At each wavelength and each level of total launched power the whole WDM grid was equalized for uniform power profile. We see that the NLT at these wavelengths is not the same and varies between 17 dBm and 20 dBm. This is attributed to the residual wavelength dependency of the channel power profiles, which is inevitable in the equalization of the recirculation loop measurements. We then selected all the waveforms at 18 dBm, post-processed them by off-line DSP, and extracted the SNR, and the dual-polarization generalized mutual information (GMI). Finally, we applied the family of the SC-LDPC FEC decoders [10] to the measured waveforms. This family consisted of codes with rates ranging from 0.4 to 0.94 with steps of 0.01. For each waveform, all rates were examined, window decoding with window size equal to 13, and 5 iterations were applied. The rate was declared successful if no error was observed over 200 code blocks. For more information please see [10]. Finally, we selected the highest successful rate, and computed the net bit rate (NBR) and achievable information rate (AIR). We have: NBR = 2*mr*x0.98x98 [Gb/s], and AIR = GMIx0.98x98 [Gb/s], where *r* is the highest successful rate, *m* = 2 for QPSK, and 6 for 64QAM, and we have accounted for 2% pilots. Fig. 3b illustrates the NBR (circles) and the AIR (upper triangles) for the three test channels at 18 dBm, and after 6050 km transmission, where we achieved the NBR of 560 Gb/s.

Next, we report on the transpacific measurements. We measured a single channel at 1542.34 nm modulated with 98 GBd PDM-QPSK, after 29 loops. At the receiver side SNR and GMI were calculated after applying offline DSP. Fig. 3c shows the SNR vs. total launched power, where the powers of all the C-band channels were swept together. At each power level, the WDM channels were carefully equalized to have flat power (cf. Fig. 1f for the typical spectrum at the loop output, after 29 loops). The NLT is between 16 dBm and 17 dBm, the optimum SNR at NLT is 7 dB, and at low powers (below 13 dBm) signal droop can be observed as the SNR vs. power curve deviates from the linear slope [11]. In these measurements, we considered the block QC-LDPC codes [12] with SNR FEC threshold of 5.9 dB, and *r* = 5/6. Fig. 3d illustrates the obtained NBR and AIR for the QPSK channel under test at various powers. In particular, we can achieve NBR equal to 320 Gb/s even at 15 dBm, *i.e.* more than 1 dB below the NLT, and with 0.6 dB of SNR margin with respect to the FEC threshold. Finally, in Fig. 4 we illustrate the amplitude magnitude of the four butterfly FIR filters of the complex 2x2 MIMO equalizer.

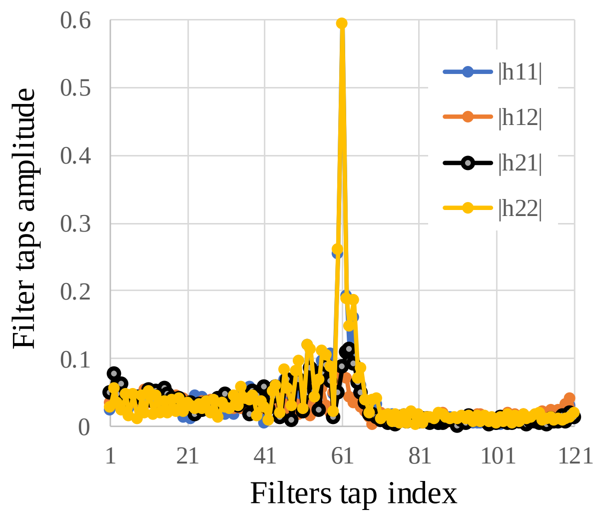

Fig. 4. Amplitude magnitude of MIMO equalizer taps

Note that, the equalizers' impulse responses are long, to compensate the impairments of the high frequency DAC, and the non-uniform phase response of the scope frontend. (cf. Fig. 3a in [6]).

4 Conclusion

In this paper we reported on power efficient transoceanic transmissions geared towards the novel design paradigm of submarine cables. At the transmitter side, the channel baud rate was pushed to 98 GBd, using novel CMOS technology for digital-to-analog convertors. At the receiver side conventional DSP was applied. In particular nonlinear compensation was avoided, and the systems was operated at the nonlinear threshold (NLT) or below the NLT. We demonstrated net 560 Gb/s transmission after 6050 km, and net 320 Gb/s transmission after 17545 km, in a full C-band WDM system experiment.

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