NET 800 GBIT/S TRANSMISSION OVER 605 KM USING 99.5 GBAUD PDM-64QAM WITH CMOS DIGITAL-TO-ANALOG CONVERTERS

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Abstract

We demonstrate the transmission over 605 km of a spectrally efficient 800 Gb/s 99.5 GBd polarization division multiplexed (PM) 64QAM channel inserted in a wavelength division multiplexed (WDM) full C-band spectrum, using high-speed CMOS digital-to-analog converters (DAC), with digital and optical spectrum optimization.

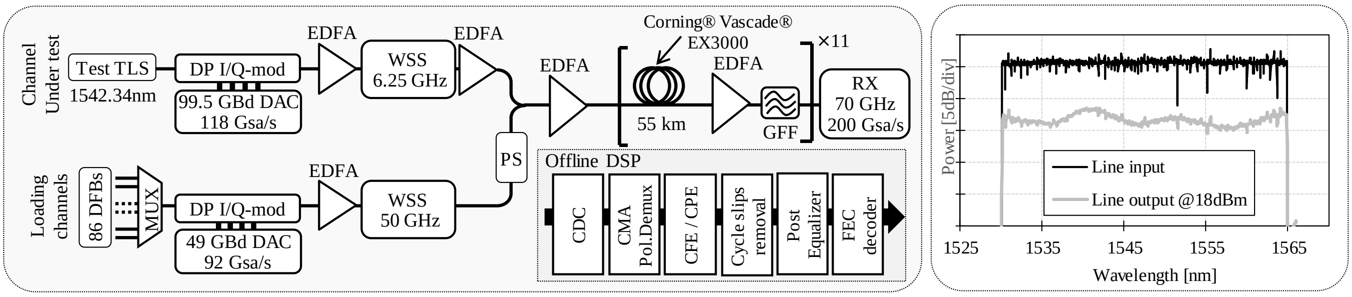
1 Introduction

Leveraging high-baudrate signal generation systems is a promising way to increase the bit rate per optical carrier while reducing the number of transceivers in optical networks. 400 Gb/s per channel coherent solutions have been recently announced for applications ranging from data-center interconnect (DCI) to long-haul transmission, together with 800 Gb/s for DCI or short-reach metro applications in the near future. In the past few years, net rates over 1 Tb/s have been demonstrated in transmission experiments using a variety of techniques for generation of high-baudrate signals. Among them, we can mention techniques for more than 100 GBd signal generation such as sub-carrier multiplexing [1], spectral sub-band combination [2], or electrical time-domain multiplexing [3]. Recently, a record full C-band WDM transmission of 1 Tb/s over 800 km has been demonstrated with an analog bandwidth extender allowing the generation of 120 GBd signal [4]. However, complex transmitter architectures involved by these techniques make their implementation very challenging for industrial applications.

Recent development in high-speed digital-to-analog converter (DAC) technologies allowed to increase bitrates without increasing transmitter complexity [5]. Bearing in mind constraints of current optical networks, we report in Table 1 two record transmission experiments [6,7] employing spectrally efficient high baudrate signals compliant with

Table 1: record transmission experiments in 100 GHz grid with CMOS high speed DAC

Net rate	680 Gb/s/channel	800 Gb/s/channel
Distance	400 km	400 km
Baudrate	66 GBd	82 GBd
Channels	1	10
Format	PCS1024QAM	PCS256QAM
Reference	[6]	[7]



(a) (b)

Fig. 1: (a) Experimental setup (TLS: tuneable laser source, DFB: distributed feedback laser, DP I/Q Mod: dual polarization in phase and quadrature modulator, DAC: digital-to-analog converter, EDFA: erbium doped fiber amplifier, WSS: wavelength selective switch, PS: polarization scrambler, GFF: gain flattening filter, RX: receiver, DSP: digital signal processing, CDC: chromatic dispersion compensation, CMA Pol.Demux: constant modulus algorithm for polarization demultiplexing, CFE/ CPE: carrier frequency and phase estimation, FEC: forward error correction); (b) WDM spectrum at line input and output.

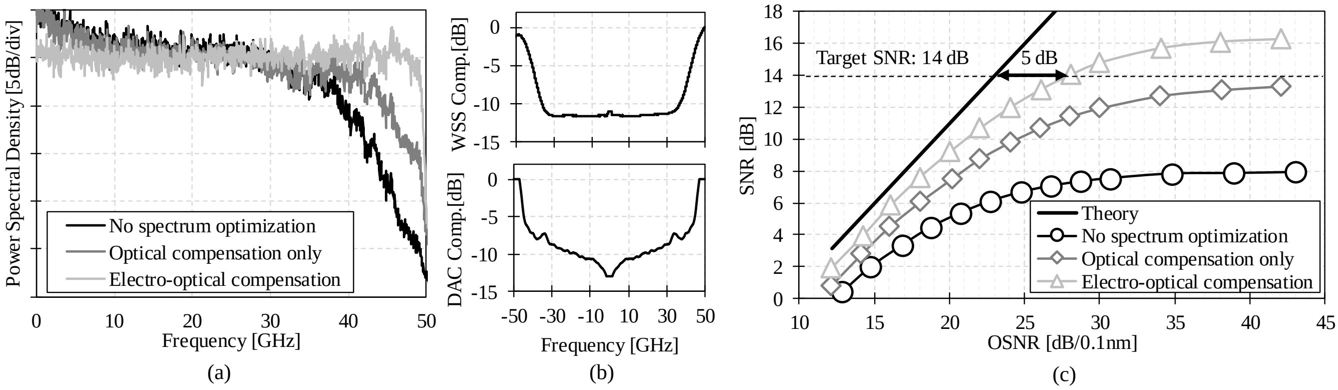


Fig. 2: (a) Power spectral density computed from received signal for non-optimized, optically compensated and electro-optically compensated signal; (b) Optical (top) and electrical (bottom) attenuation profiles applied with WSS and DAC respectively; (c) SNR vs OSNR back-to-back performance for non-optimized, optically and electro-optically compensated signal.

standard 100 GHz spacing and using CMOS DAC technology, particularly suitable for large-scale production. These experiments use probabilistic constellation shaping (PCS) techniques to maximize spectral efficiency and achieve transmissions over 400 km of 680 Gb/s with a single 66 GBd channel and 800 Gb/s per carrier with 10 WDM 82 GBd channels.

In this work, we use state-of-the-art commercially available Fin field-effect transistor (FinFET) CMOS DAC operating at 118 GSa/s to generate 99.5 GBd polarization division multiplexed (PDM) 64QAM signals. Bandwidth limitation issue of electrical amplifiers and electro-optical modulators is addressed with a digital and optical spectrum optimization scheme [8]. Employing low-loss Corning EX3000 55 km fiber spans and erbium doped fiber amplifiers (EDFA), we insert our 100 GHz channel in a full C-band WDM transmission and demonstrate a net transmission of 800 Gb/s per channel over 605 km.

2 Experimental setup

Our experimental setup depicted in Fig.1a is made of one channel under test at 1542.34 nm and 86 laser sources in C-band separated by 50 GHz. The channel under test is modulated with a dual polarization in phase and quadrature (DP I/Q) Lithium Niobate modulator driven by a DAC operating at 118 GSa/s and loaded with 99.5 GBd 64QAM randomly generated sequences. In order to compensate for the limited electro-optical bandwidth, the signal is optically shaped thanks to a 6.25 GHz-grid-resolution wavelength selective switch (WSS) and amplified by EDFA to overcome optical loss in the WSS (more details in next section). The loading channels are separately modulated with a DP I/Q modulator operating at 92 GSa/s and fed with 49 GBd 64QAM 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 100 GHz slot of the channel under test. A polarization scrambler (PS) ensures a variable random state of polarization of the loading signal before coupling the loading channels to the channel under test. The WDM signal is then amplified by a last EDFA before being sent into the transmission line. The WDM spectrum at the line input, measured with an optical spectrum analyzer (OSA), is shown (black curve) in Fig.1b. The transmission line is made of 11 spans of 55 km EX3000 fiber followed by EDFA with output power ranging from 15 to 20 dBm. A gain flattening filter (GFF) is used after each EDFA to equalize the power profile over the C-band. The signal at the line output, for a total launched power of 18 dBm, is shown (grey curve) in Fig.1b. At the receiver (RX), the channel under test is extracted with a 50 GHz-grid-resolution WSS, amplified and sent to the coherent receiver including a coherent mixer, a local oscillator, balanced photodiodes and a 70 GHz bandwidth high speed sampling scope operating at 200 GSa/s. Data sets of 2 million samples are stored and offline DSP is performed. After electronic chromatic dispersion compensation (CDC), the polarization demultiplexing is performed by blind constant modulus algorithm (CMA), followed by classical carrier frequency and phase estimation (CFE/CPE). Cycle slips are detected and removed with the help of 1% QPSK pilot symbols inserted in the 64QAM sequences. A least-mean square symbol-spaced blind equalization is used before signal-to-noise ratio (SNR) estimation and decoding by spatially coupled low density parity check (SC-LDPC) forward error correction (FEC) codes [9] to determine the maximum code rate resulting in error-free transmission.

3 High-baudrate spectrum optimization

In this work, high baudrate signal transmission challenges us to tackle the bandwidth limitation of the electrical driver and electro-optical modulator. As shown in Fig.2a, the power spectral density (PSD) of the received signal, in the absence of any equalization (black line), is severely degraded: the impairment over the 49.75 GHz electrical bandwidth of the signal indeed exceeds 25 dB. Since using only digital compensation to overcome this limitation would impose an unacceptable loss of effective number of bits (ENOB) of the DAC [8], we use here a 6.25 GHz-grid-resolution standard WSS to emphasize the signal at the edges of the band, as depicted by the ASE response of the WSS profile shown in Fig.2b (top). With a flat attenuation of 12 dB in the central part of the spectrum, and smoothed to 0 dB at 50 GHz, the optically compensated power spectral density is shown in dark grey line in Fig.2a. The degradation over the band is now limited to 15 dB. Then we precisely measure the optical spectrum of the signal with a fine resolution OSA and compute the digital pre-compensation profile shown in Fig.2b (bottom), which is required to flatten the spectrum over the whole bandwidth. The resulting power spectral density is shown in light grey line in Fig.2a.

We show in Fig.2c the back-to-back performance characterization of the single 99.5 GBd PDM-64QAM channel, as a function of the optical signal to noise ratio (OSNR), for the different above-mentioned cases: raw signal without any spectrum optimization (black line with circle markers), optical band edge emphasis only (dark grey line with diamonds) and combined optical and digital compensation (light grey line with triangles). Without any compensation, the SNR performance does not exceed 8 dB. The optical compensation enables to reach an SNR of 13 dB at maximum OSNR. With the use of digital pre-emphasis and optical compensation, the SNR plateau exceeds 16 dB, and the penalty compared to the theoretical curve for flat 99.5 GBd signal is limited to 1 dB for 6 dB SNR in linear regime, and 5 dB for the 14 dB SNR we targeted in the transmission case.

4 Transmission results

The channel under test is now coupled to the loading channels as described before and sent to the transmission line. Fig.3a shows the SNR versus total launched power after 605 km. The total launched power was varied in the transmission line from 15 to 20 dBm by changing the driving currents of all EDFAs. The non-linear threshold (NLT) in this experiment is 18 dBm, and the optimum SNR at NLT is around 14 dB. Fig.3b shows the SNR as a function of the transmission distance. The distance was swept by measuring the signal after each 55 km span, for a fixed total launched power of 18 dBm, set to the NLT previously found. The performance at 0 km is 14.7 dB, meaning that a 1.3 dB penalty is caused by the coupling of the channel under test to the loading channels, compared to the best back-to-back performance. The SNR then decreases steadily to 14.0 dB at 605 km. We apply SC-LDPC FEC decoders [9] to the signals obtained after the previously described DSP. We have a family of codes with rates ranging from 0.4 to 0.91, with steps of 0.01. We find the FEC with highest rate resulting in error-free transmission, for each distance and each total launched power. Fig.4a shows net bit rate (circles) and achievable information rate (AIR) (triangles) vs. the total launched power for 605 km transmission. AIR is computed from the measured Generalized Mutual Information

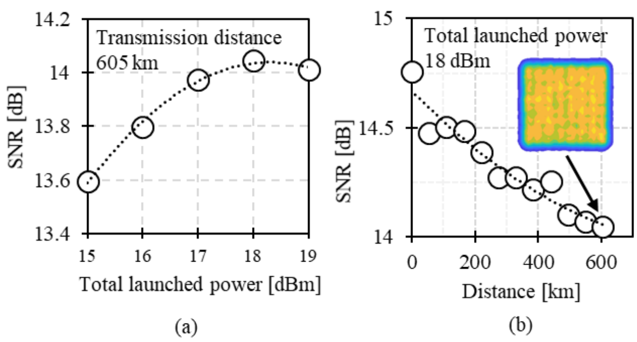


Fig. 3: Evolution of SNR as a function of the fiber total launched power, for a transmission distance of 605 km (a), and as a function of transmission distance, for a total launched power of 18dBm (b).

(GMI) extracted from the resulting constellation and represents the achievable net bit rate assuming ideal FEC decoding. The labels indicate the maximum rates ensuring error-free transmission. For a total launched power corresponding to the NLT or (NLT+1) dBm, the highest code rate is 0.68. With 1% pilot symbols, the resulting net rate is 99.5 GBd×6 b/symbol×2×(1 - 0.01)×0.68=804 Gb/s, with a penalty of 51 Gb/s compared to AIR due to FEC implementation penalty. Fig.4b shows the evolution of the net bit rate as a function of the transmission distance. At 55 km, highest code rate is 0.71 and net rate is 839 Gb/s, scaling down to 827 Gb/s up to 220 km with 0.70 code rate, 816 Gb/s up to 440 km with 0.69 code rate and 804 Gb/s from 495 to 605 km as previously described.

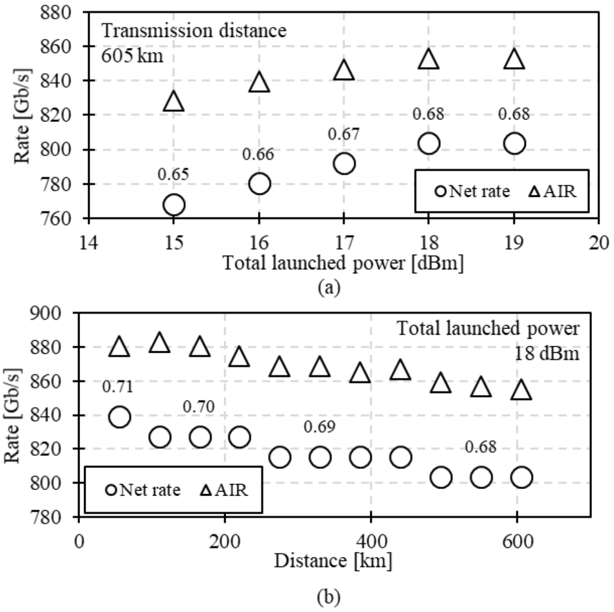


Fig. 4: Evolution of net bit rate and AIR as a function of the total launched power, for a transmission distance of 605 km (a) and as a function of transmission distance, for a total launched power of 18dBm (b).

5 Conclusions

We demonstrated an 800 Gb/s PDM-64QAM signal transmission in a full C-band WDM spectrum, over 605 km EX3000 fiber and using EDFA amplification. We generated our 99.5 GBd signal compatible with 100 GHz spacing grid using CMOS high-speed DAC, digital and optical spectrum equalization with standard WSS to overcome electro-optical bandwidth limitations. We demonstrated a spectrally efficient transmission with low complexity and commercially available DAC, compliant with future 800 Gb/s standards in regional optical networks.

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