16x125 Gb/s Quasi-Nyquist DAC-Generated PM-16QAM Transmission Over 3590 km of PSCF

16x125 Gb/s Quasi-Nyquist DAC-Generated PM-16QAM Transmission over 3,590 km of PSCF

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***Abstract*—We report on a transmission experiment over high-performance pure-silica core fiber (PSCF) of 16 Nyquist wavelength-division-multiplexed (Nyquist-WDM) channels at a symbol rate of 15.625 GBaud, using polarization-multiplexed (PM) 16-symbols quadrature-amplitude-modulation (16QAM), resulting in a per-channel raw bit-rate of 125 Gb/s. The channel spacing was 16 GHz, corresponding to 1.024 times the symbol rate. The interchannel crosstalk penalty was drastically reduced through the confinement of the signal spectrum within a near-Nyquist bandwidth, achieved with digital filtering and digital-to-analog converters (DACs) operating at 1.5 samples/symbol. The optical line was a recirculating loop composed of two spans of high-performance PSCF with erbium-doped fiber amplifiers (EDFA) only. The transmission distance of 3,590 km at a target line bit-error rate (BER) of 1.5·10^{-2} was achieved at a raw spectral efficiency (SE) of 7.81 b/s/Hz. Assuming a commercial hard FEC with 20.5% redundancy, capable of handling the target BER, the net SE was 6.48 b/s/Hz, the highest so far reported for multi-thousand km transmission of PM-16QAM at ≥100 Gb/s per channel. These results demonstrate the feasibility of very high spectral-efficiency DAC-enabled ultra-long-haul quasi-Nyquist-WDM transmission using PM-16QAM with today's available technologies and manageable DSP complexity.**

***Index Terms*—Optical communications, coherent detection, quadrature amplitude modulation (QAM), wavelength division multiplexing (WDM), Nyquist-WDM**

I. Introduction

SPECTRALLY efficient modulation formats are today under intense investigation. Polarization-multiplexed quadrature phase-shift keying (PM-QPSK) has been shown to allow ≥100 Gb/s per channel full C-band transmission over transoceanic distance, with a channel spacing as low as the symbol rate [1], [2], thus delivering its Nyquist-limited theoretical gross spectral efficiency (SE) of 4 b/s/Hz even at such long distance. Encouraged by these results, the focus of system researchers has recently shifted to higher-cardinality constellations.

In particular, PM-16QAM is currently considered as the most interesting upgrade with respect to PM-QPSK, due to its double gross theoretical SE at the Nyquist limit (8 b/s/Hz). Consequently, several experiments have been carried out of late on high-SE PM-16QAM. In these experiments, tight channel confinement was obtained either through optical spectral shaping, such as [3], or through DAC signal generation, such as [4].

In this paper we report on a transmission experiment based on signals generated through digital signal processing (DSP) and digital to analog converters (DACs), with a raw bit rate per channel of 125 Gb/s. The channel power spectra were nearly-rectangular (raised cosine with roll-off 0.01). The optical link used for the propagation tests was designed as a typical submarine system link, with EDFA-only amplification and an average span length of 54.42 km. The fiber was advanced PSCF fiber with low-loss and low non-linearity coefficient.

The system reached 3,590 km, at a bit-error rate (BER) of 1.5·10^{-2}. The channel spacing for the wavelength-division multiplexed (WDM) signals was 1.024 times the symbol rate, achieving a gross SE of $7.81\ \mathrm{b/s/Hz}$. Assuming a commercial hard forward error correction (FEC) code with 20.5% redundancy [5], which is capable of handling a bit-error-rate BER=1.5·10^{-2}, the net SE was 6.48 b/s/Hz, the highest so far reported for multi-thousand km transmission of PM-16QAM at ≥ 100 Gb/s per channel. The net spectral-efficiency-times-distance product (SEDP) was 23,275 b/s/Hz·km.

Higher SEDPs with PM-16QAM have been reported in [6] (35,672 b/s/Hz·km) and [7] (47,851 b/s/Hz·km), although with lower net SEs (5.2 and 4.7 b/s/Hz). Comparisons are however very difficult, because of several differing aspects. Both [6] and [7] assumed sophisticated soft FECs resulting in higher target operating BERs than this experiment, granting about 1.5 and 2 dB better sensitivity, respectively. [6] used a larger effective area fiber, while it covered a much wider portion of the C-Band (3 THz). It also used return-to-zero pulse carving with optical spectral shaping, rather than transmitter (Tx) DSP and DAC. [7] employed orthogonal-frequency-division-multiplexing (OFDM) rather than serial transmission, over 1 THz bandwidth, and it also assumed receiver (Rx) DSP non-linearity (NL) compensation.

In this experiment, we concentrated on options that would make the system easier to commercially exploit today, including less sophisticated FECs, no NL compensation and a low (for serial transmission) Tx DAC rate of 1.5 samples/symbol. As a whole, we believe this experiment demonstrates the feasibility of ultra-long-haul PM-16QAM quasi-Nyquist-WDM transmission through DAC-enabled spectral shaping, at an extremely tight channel spacing and high net SE, with manageable DSP complexity and without the need of any optical filter at the Tx side for channel confinement. The substantial SEDP reached by the experiment proves that the high SE was achieved without compromising performance.

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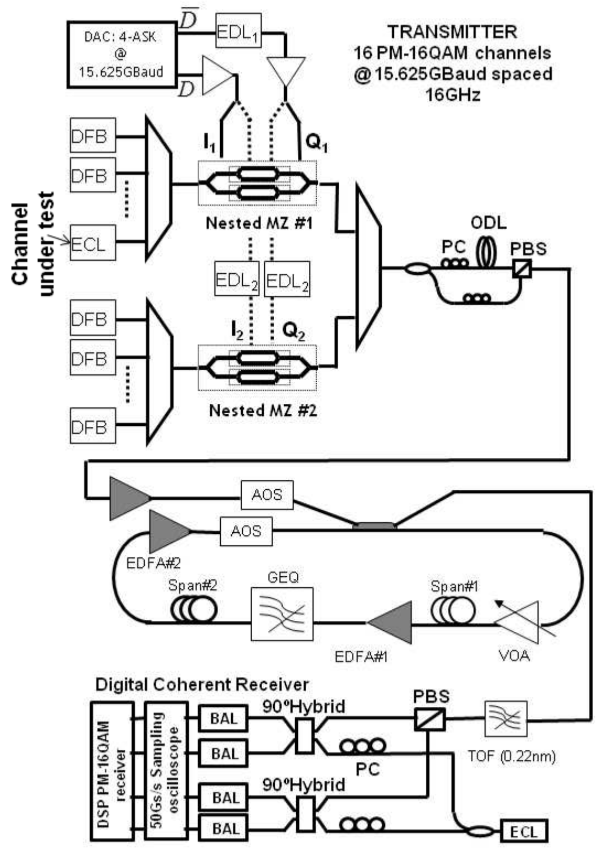

Fig. 1. The transmission experiment test-bed.

A preliminary version of this experiment was reported in [4]. However, there the system operated at 14 GBaud, resulting in a net per-channel bit-rate of 93 Gb/s which fell short of the target 100 Gb/s. In addition the channel spacing was larger (1.05 times the symbol rate).

II. Experiment Setup

The system setup is shown in Fig. 1. An array of 16 distributed-feedback (DFB) lasers between 1556.0 nm and 1558.5 nm was finely tuned at 16 GHz frequency separation. Note that, when performing BER measurements, the Tx laser of the channel under test was replaced by an external cavity laser (ECL). The odd and even carriers were separately fed to two distinct nested Mach-Zehnder modulators (NMZM). The electrical signals driving the NMZMs were obtained as follows.

Two distinct (2^{15}-1) pseudo-random binary sequences (PRBSs) were generated on a computer. They were combined to form a 4-level amplitude-shift keying (ASK) signal with non-return-to-zero symbols. The 4-ASK signal was then digitally filtered to give it a sharp square-root raised-cosine spectral shape, with electrical bandwidth equal to half the symbol rate. The samples of the filtered 4-ASK signal were then fed to a DAC running at 23.4375 GS/s, i.e., at 1.5 samples per symbol. Specifically, we used an arbitrary waveform generator (AWG) Tektronix 7122B with ten nominal resolution bits and bandwidth equal to 9.6 GHz.

The I and Q driving signals for the even-channels NMZM were obtained from the two complementary outputs of the DAC, with the insertion of 85 symbols delay on the quadrature arm for decorrelation (electrical delay line, EDL1 in Fig. 1). Both in-phase and quadrature electrical signals were further split and delayed (EDL2 in Fig. 1) by 134 symbols to generate the driving signals for the odd-channel NMZM. No compensation of the non-linear characteristic of the NMZMs was performed in the DSP, since the NMZMs were driven in the linear region of their electro-optic characteristic: the modulation depth on I & Q arms for both the NMZMs was approximatively 25%.

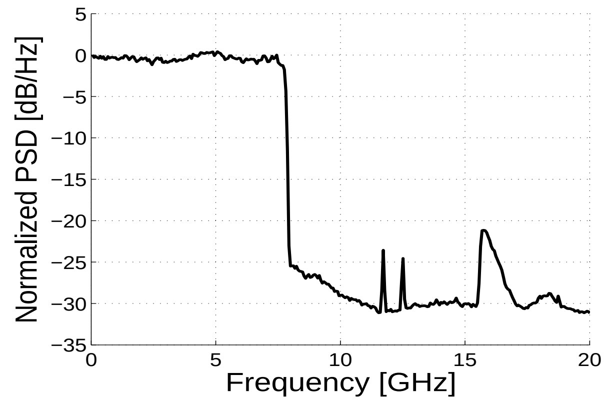

Fig. 2. Power spectrum of the 15.625 GBaud 4-ASK electrical signal at the nested Mach-Zehnder modulator inputs.

The 4-level ASK signals measured at the NMZMs input exhibit an electrical power spectrum characterized by a very flat top and an extremely sharp cut-off, as shown in Fig. 2. The flatness was achieved by DSP pre-compensation of the frequency response of the overall electrical chain. The sharp cut-off was obtained by imposing a roll-off equal to 0.01 through digital filtering. Note that a residue of the first aliasing copy of the spectrum shows up in Fig. 2 as a triangular-shaped wedge with a peak at about 16 GHz. The overall electrical SNR of the useful signal at the input of the modulator, measured on the scattering diagram of the constellation after equalization, was approximately equal to 15 dB.

Finally, even and odd channels were optically coupled with a polarization maintaining 3dB coupler. The resulting 16-channel single-polarization optical signal was split and recombined onto two orthogonal polarizations for PM emulation, with one polarization going through 64 m of a fiber optical-delay-line (ODL in Fig. 1) for decorrelation. No optical filtering was applied at the transmitter side. The power spectrum of the PM-16QAM Nyquist-WDM signal at the transmitter output is shown in Fig. 3, obtained with an optical spectrum analyzer resolution of 0.1 nm.

The WDM signal was launched into a re-circulating fiber loop consisting of two spans of uncompensated PSCF, with length 54.04 and 54.79 km. The PSCF had an average fiber loss of $0.162\ \mathrm{dB/km}$, a chromatic dispersion at 1550 nm of $21\ \mathrm{ps/nm/km}$, with dispersion slope $0.061\ \mathrm{ps/nm^2/km}$. The effective area was $130\ \mu\mathrm{m}^2$. The loop made use of EDFA-only amplification and included a gain-equalizer (GEQ).

The optical receiver had a standard set-up for coherent reception, with a tunable external-cavity laser (ECL) as local

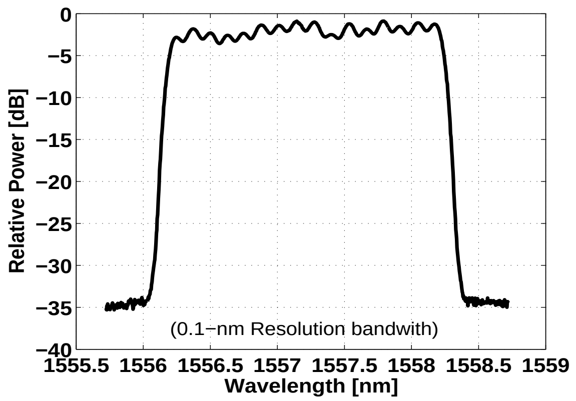

Fig. 3. Power spectrum of the optical WDM 16-channel signal (0.1nm resolution)

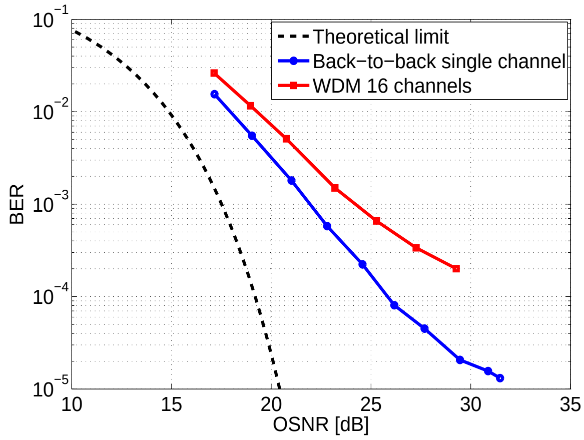

Fig. 4. Back-to-back BER vs. OSNR (over 0.1 nm), center channel.

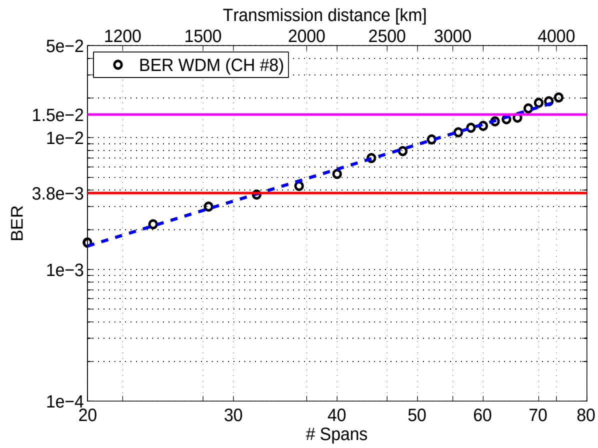

Fig. 5. BER vs. number of spans for the center channel, at the optimum launch power of -6 dBm per channel.

oscillator (LO) and a standard optical hybrid for signal and LO mixing. The eight outputs of the hybrid were connected to linear-amplified dual-balanced photodetectors with 30 GHz bandwidth. Channel selection was done by tuning the LO frequency near the center frequency of the received channel to be measured. The four electrical signal outputs of the photodetectors were first filtered using 7.46 GHz 4-pole Bessel filters and then sampled at 50 GS/s using a Tektronix DPO71604 real-time oscilloscope.

The off-line receiver DSP consisted of the following functional blocks. First, a re-sampling stage lowered the sample rate from 3.2 samples per symbol down to 2. Then, a first equalizer stage performed bulk CD compensation, followed by a multiple-input, multiple-output (MIMO) equalizer stage, adjusted through a multi-modulus constant modulus algorithm (MM-CMA) [8]. Frequency offset estimation and compensation was then performed through a Viterbi&Viterbi stage, modified to properly filter out the 16QAM modulation [9]. Finally, minimum distance decision was performed.

Tx and LO lasers were two distinct ECLs, with a linewidth of less than 100 kHz each. At the Tx, the ECL was tuned to replace in turn each DFB source, for BER measurement. At the Rx input, we inserted a tunable optical filter (TOF) with bandwidth 0.22 nm, to prevent excessive optical power from reaching the photodetectors.

III. Results

The back-to-back (btb) BER vs. optical signal-to-noise ratio (OSNR) performance is reported in Fig. 4. For the analysis of the experimental data, we considered two different FEC threshold BERs: $3.8 \cdot 10^{-3}$, corresponding to a standard hard-FEC with 7% overhead, and $1.5 \cdot 10^{-2}$, achievable either with soft FECs [10] or with advanced commercial hard FECs [5] with 20.5% overhead. The penalty between single-channel and WDM transmission, at the FEC threshold BERs of $3.8 \cdot 10^{-3}$ and $1.5 \cdot 10^{-2}$ was respectively 1.6 dB and 1 dB. Such penalty is mild, considering the quasi-Nyquist spacing, confirming that DAC-enabled spectral engineering effectively limits inter-channel linear crosstalk, thus allowing the use of extremely tight channel spacing. Such penalty was mostly due to the residual aliasing taking place at the Tx, previously mentioned while commenting Fig. 2, that occurs due to the low DAC sample rate (1.5 samples/symbol). At the FEC threshold of BER=$1.5 \cdot 10^{-2}$, the overall btb OSNR penalty between WDM transmission and ideal system performance was 4.2 dB.

To explore the reach potential of the system, BER degradation vs. number of spans was measured for the center channel of the WDM grid, at the measured optimum launch power of -6 dBm per channel (Fig. 5). The signal constellations both in btb and after transmission over 32 spans are shown in Fig. 6.

Two BER measurements among all channels were carried out at the number of recirculations corresponding to the two FEC threshold BERs of $3.8 \cdot 10^{-3}$ and $1.5 \cdot 10^{-2}$. The results are shown in Fig. 7, which displays the measured BER on all 16 channels after 16 and 33 recirculations (32 and 66 spans), corresponding to 1,741 and 3,591 km, respectively. All measurements were carried out at the optimum launch power of -6 dBm per channel, over 1,600,000 bits (200,000 symbols). Using the technique described in [11], polarization dependent loss (PDL) was constantly monitored through the processing of the Rx adaptive equalizer coefficients. No value higher than 1.5 dB was found during the measurements.

The transmission capacity achieved assuming 7% FEC

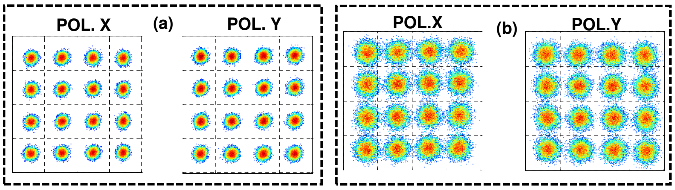

Fig. 6. Recovered x-axis and y-axis constellations on the center channel, during WDM transmission, (a) in btb, (b) after 32 spans (at -6 dBm per channel).

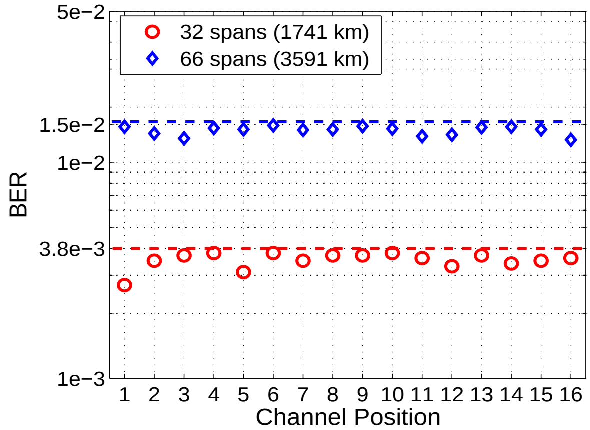

Fig. 7. 16-channel BERs at 32 and 66 spans, at the optimum launch power of -6 dBm per channel.

overhead, was a net SE of 7.30 $\mathrm{b/s/Hz}$, with a corresponding net SE-distance-product (SEDP) of $12,714$ $\mathrm{b/s/Hz \cdot km}$. Considering 20.5% overhead the net SEDP moved to $23,284$ $\mathrm{b/s/Hz \cdot km}$ (net SE of 6.48 $\mathrm{b/s/Hz}$).

The transmission distances achieved in the experiment are in line with expectations from simulations and analytical results: in fact, using the GN model [12], the predicted maximum distance for a system with the parameters of the experimental setup described in Section II is 67 spans at BER=$3.8{\cdot}10^{-3}$ and 33 spans at BER=$1.5{\cdot}10^{-2}$, for an optimum launch power of -6 dBm.

IV. Comments and Conclusion

A highest-to-date gross SE of 7.81 b/s/Hz (for ultra-long-haul WDM PM-16QAM system experiments operating at $\geq$100 Gb/s per channel) was achieved through the use of DSP and DAC technology, demonstrating the feasibility of close-to-rectangular (roll-off 0.01) signal spectrum generation with extremely tight, quasi-Nyquist, channel spacing (1.024 times the symbol rate).

One interesting aspect of this result is that the DAC operated at the low sample-rate of 1.5 samples/symbol. While simple non-return-to-zero pulse generation is feasible even down to 1 sample/symbol, accurate spectral shaping demands sample rates substantially greater than the symbol rate, to thwart aliasing. Nonetheless, our results show that 1.5 samples/symbol are enough to ensure mild WDM penalties (1 dB), provided that the electrical network is designed so as to sufficiently remove aliasing.

Despite the quasi-Nyquist spectral packing, long-haul transmission performance was not impaired and a transmission distance of 3,590 km was achieved, consisting of 66 spans of high-performance PSCF with EDFA-only amplification, at BER=$1.5 \cdot 10^{-2}$. A substantial net SEDP of 23,284 b/s/Hz·km was obtained.

This was a significant result, but there is clearly margin for improvement. Specifically, the btb performance was about 4.2 dB away from theoretical. This penalty was mostly due to transmitter-side non-ideal performance, whereas the receiver contribution was very small. Exploiting currently available technology and leveraging on dedicated design, a practical implementation could improve the Tx by using lower noise and more linear drivers, and sharp anti-aliasing electrical filters.

If so, substantial operational margin could be gained and target distances on the order of a few thousand km would be commercially possible with quasi-Nyquist WDM PM-16QAM systems, at net spectral efficiencies in excess of 6 b/s/Hz, while still relying on hard FECs and moderate DSP complexity.

V. Acknowledgments

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