# 1.5-Tb/s Guard-Banded Superchannel Transmission over 56× 100-km (5600-km) ULAF Using 30-Gbaud Pilot-Free OFDM-16QAM Signals with 5.75-b/s/Hz Net Spectral Efficiency

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**Abstract** *We transmit a 1.5-Tb/s guard-banded superchannel, consisting of eight all-electronically-generated 30-Gbaud pilot-free PDM-OFDM-16QAM signals spaced at 32.8 GHz, over 5600-km ULAF, achieving the highest spectral-efficiency-distance product of over 32,000 km·b/s/Hz for Tb/s-class superchannel transmission with >5 b/s/Hz net spectral efficiency.*

## Introduction

Terabits/sec (Tb/s) superchannel transmission has recently attracted much attention [1-6] as it brings several key system benefits, including improved spectral efficiency as compared to conventional wavelength-division multiplexing (WDM) and enhanced compatibility with large-scale photonic integration. Seamless multiplexing of modulated signals using optical orthogonal frequency-division multiplexing (OFDM) has been used to generate high spectral efficiency superchannels, but it requires the use of frequency-locked carriers which reduces its scalability and flexibility. Quasi-Nyquist WDM has been introduced to allow the use of independent frequency-unlocked lasers at the expense of slightly reduced spectral efficiency [3]. 1-Tb/s quasi-Nyquist super-channels consisting of polarization-division multiplexed (PDM) 16-QAM signals have been transmitted over 2400 km of 50-km fiber spans [5] and over 640 km of 80-km fiber spans [6] with a spectral efficiency of 5 b/s/Hz. The highest all-electronic OFDM bit rates [7,8] were

limited to ~100 Gb/s due to the inavailability of higher-speed digital-to-analog converters (DACs). Here, we demonstrate the all-electronic generation of 30-Gbaud PDM-OFDM-16QAM using two novel 10-bit-resolution DAC prototypes operating at 50 GS/s. The resulting bit rate of 233 Gb/s is more than twice the previous records [7,8]. We then perform transmission of a 1.5-Tb/s guard-banded OFDM superchannel consisting of eight such signals, packed at a net spectral efficiency of 5.75 b/s/Hz using unlocked lasers. A novel decision-directed approach is used to allow pilot-free OFDM transmission [9]. The superchannel is transmitted over 56 100-km ultra-large-area fiber (ULAF) spans. Soft-decision forward error correction (SD-FEC) is implemented using offline processing as an inner code, resulting in a corrected bit-error ratio (BER) below the threshold of an outer hard-decision (HD) decoder to achieve a record spectral-efficiency-distance product (SEDP) of >32,000 km·b/s/Hz for Tb/s-class superchannel transmission with >5 b/s/Hz net spectral efficiency.
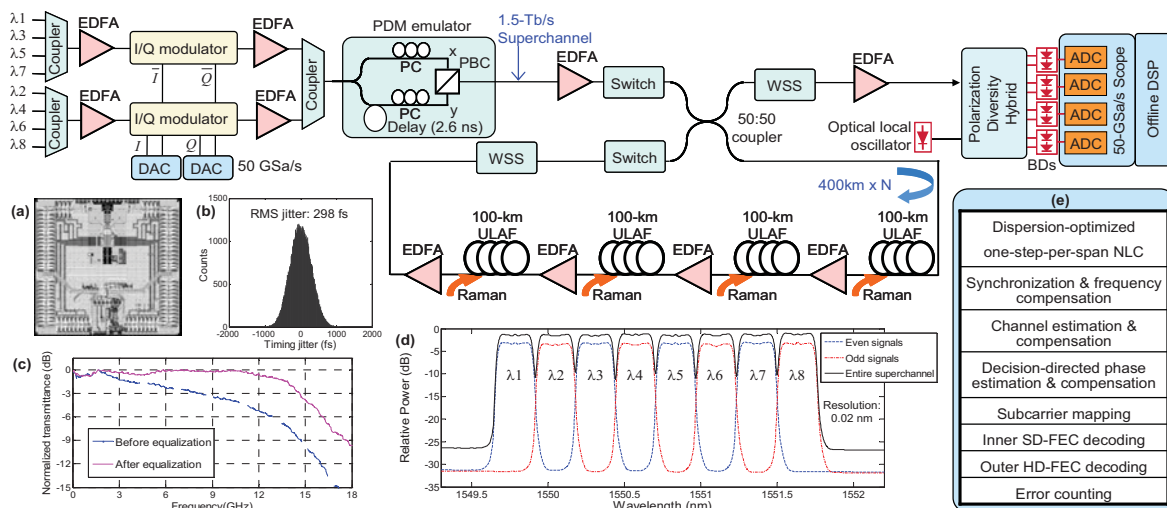


**Fig. 1:** Schematic of the experimental setup. Insets: (a) Layout image of a 50-GS/s DAC; (b) measured inter-DAC timing jitter distribution; (c) measured DAC frequency response; (d) measured spectra of even signals, odd signals, and entire superchannel; (e) receiver DSP diagram. BDs: balanced detectors.

## Experimental Setup

Figure 1 shows the schematic of the experimental setup. Eight 32.8-GHz spaced external cavity lasers were separated into odd and even signal groups, which were modulated by two I/Q modulators. The two drive signals for the first I/Q modulator were provided by two DAC (inset (a)) prototypes, which were synchronized with a RMS timing jitter of less than 300 fs (inset(b)). The two drive signals for the second modulator were the complementary outputs from the same two DACs. The inputs to the DACs were provided by a field-programmable gate array (FPGA) based real-time logic circuit with stored OFDM-16QAM waveforms [10]. To generate the signal waveforms, pseudo-random bit sequences (PRBS) of length $2^{15}-1$ were first encoded and mapped to 16-QAM symbols. The IFFT size was 128, and the guard interval was 2 samples. An OFDM symbol contained 76 data subcarriers (SCs), 1 unfilled center SC, and 51 unfilled edge SCs, resulting in a 30-Gbaud signal. Four correlated training symbols were used for every 960 payload symbols. The drive waveforms were pre-equalized to compensate for frequency roll-off of the DAC (inset (c)). The modulated odd and even channels were delay decorrelated by >4 ns and passively combined by a 2×2 optical coupler, followed by polarization multiplexing, as shown in Fig. 1. The guard band between two adjacent 30-Gbaud signals was 2.8

GHz, which limits the coherent crosstalk between the signals and readily allows for efficient sub-band signal processing [11]. A low-density parity check (LDPC) code with a rate of 0.864 was implemented for the inner SD-FEC, and a typical 7%-overhead HD-FEC code was assumed as the outer code [12]. The LDPC inner code had a variable node degree distribution of $\lambda(x) = 0.15x^2+0.39x^3+0.03x^7+0.43x^8$ and a check node degree distribution of $\rho(x) = 0.015x^{27}+0.975x^{28}+0.01x^{29}$. The overall FEC overhead was 23.46%. The net superchannel data rate was 1.51 Tb/s, using an optical spectral bandwidth of 262.5 GHz, which is compatible with the new ITU standard on flexible grid WDM with 12.5-GHz granularity [13]. The channel spectral efficiency was 5.75 b/s/Hz.

The superchannel was launched into a re-circulating loop consisting of four 100-km ULAF spans with 19.7-ps/nm/km dispersion. Each span was amplified by a hybrid Raman/Erbium-doped fiber amplifier (EDFA). The average span loss was ~19 dB, and the Raman gain per span was ~8 dB. After transmission, each of the signals was sent to a digital coherent receiver with offline digital signal processing (DSP). The sampling rate of the analog-to-digital convertors (ADCs) was 50 GS/s, the same as that of the DAC. The offline DSP includes a dispersion-optimized 1-step-per-span nonlinear compensation (NLC) in which a pre-dispersion
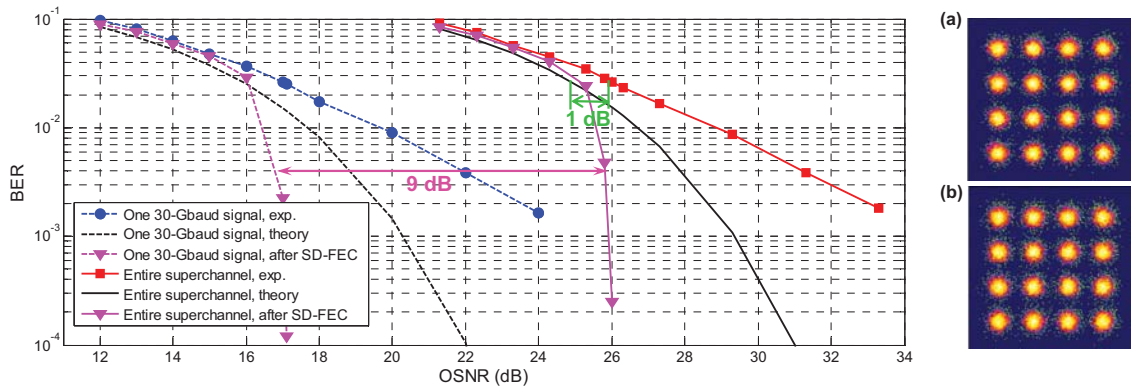


**Fig. 2:** Measured back-to-back BER performance of the 1.5-Tb/s superchannel before and after the SD-FEC decoding. The performance of a single 30-Gbaud signal is also plotted for comparison. Insets: recovered subcarrier constellations before multiplexing (a) and after the guard-banded multiplexing (b).
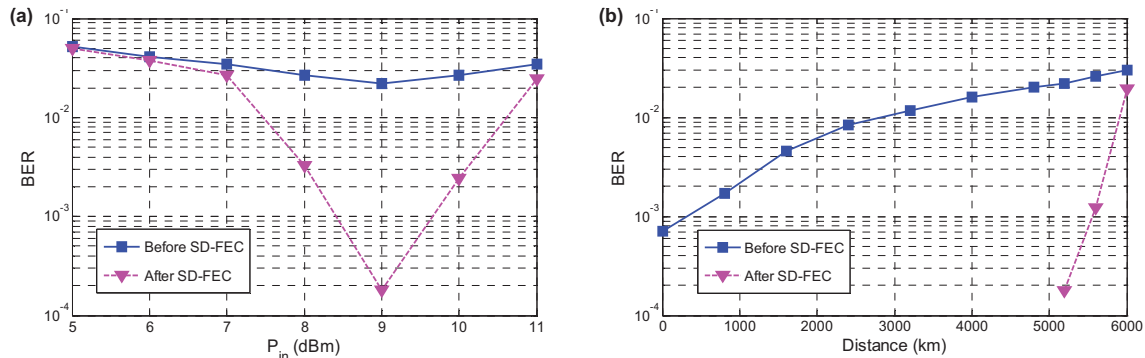


**Fig. 3:** Measured BER versus superchannel power at 5200 km (a) and versus distance at $P_{in}$=9 dBm (b).
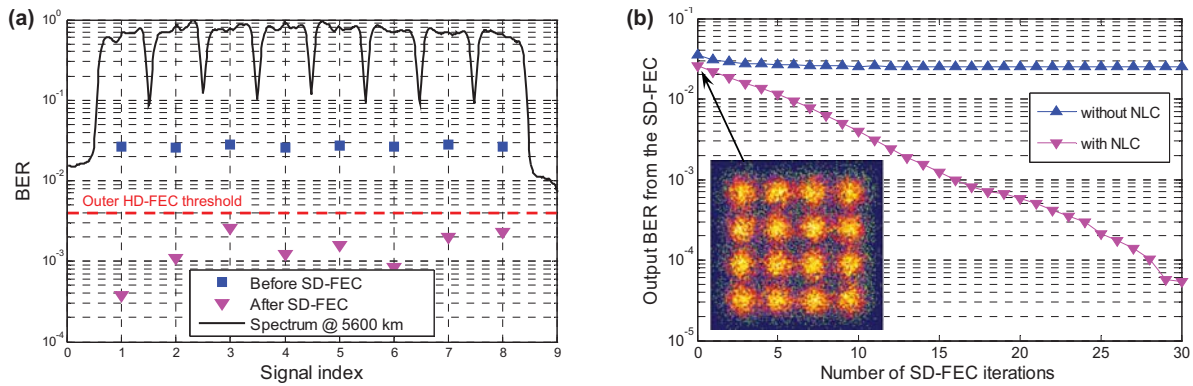
**Fig. 4:** (a) Measured BER of all the signals inside the superchannel after 5600-km transmission with $P_{in}$=9 dBm; (b) The output BER from the SD-FEC decoder (for the 4th signal) versus the number of iterations used.

compensation of 1780 ps/nm was applied so that the NLC was done to the beginning portion of each of span where signal power was high. Decision-directed phase compensation, initiated by the training symbols, was used to realize pilot-free phase estimation [9]. The SD-FEC decoding was performed using the same methodology reported in [12].

**Experimental Results**

Figure 2 shows the back-to-back BER performance of the 1.5-Tb/s superchannel. Remarkably, there is essentially no extra penalty due to guard-banded multiplexing, thanks to the intrinsic Nyquist-like spectral shaping of OFDM. For the output BER of the SD-FEC decoder to be below the correction threshold of the outer HD-FEC of $4\times10^{-3}$ [12] for a final BER of $<10^{-15}$, the input BER of the SD-FEC needs to be $<2.7\times10^{-2}$ when 15 decoder iterations were used. At this SD-FEC threshold, the required optical signal-to-noise ratio (OSNR) is ~26 dB, indicating a hardware implementation penalty of ~1 dB. Figure 3 (a) shows the measured BER of the 4th signal versus the superchannel launch power per span ($P_{in}$) at a distance of 5200 km before and after SD-FEC decoding. 52-step NLC with optimized compensating nonlinear phase shift ($\Phi_{NLC}$) was applied. The optimum signal power is 9 dBm, and the power margin, defined as the allowed power range that gives below-threshold BER values, is ~2 dB. At $P_{in}$=9 dBm, the $Q^2$-factor improvement obtained by the NLC was found to be ~0.6 dB, $\Phi_{NLC}$ was 0.6 rad. Fig. 3 (b) shows the BER as a function of transmission distance at $P_{in}$=9 dBm. Evidently, below-threshold BER has been achieved for transmission distance up to 5600 km.

Figure 4 (a) shows the measured BER of all eight 30-Gbaud PDM-OFDM-16QAM signals that made up the 1.5-Tb/s superchannel after 5600-km transmission at $P_{in}$=9 dBm. The output BER from the SD-FEC is below the outer HD-FEC threshold for each of the eight signals. The superchannel spectrum after 5600 km

transmission is also shown (0.02-nm resolution). The OSNR after the transmission was ~29.5 dB, implying a transmission penalty of ~3.5 dB. Fig. 4 (b) shows the output BER of the SD-FEC decoder versus the number of iterations used for the 4th signal after 5600-km transmission at $P_{in}$=9 dBm. Without NLC, the inner soft-decoder failed. With NLC, below-threshold BER was obtained after 10 iterations, and improved performance was obtained after more iterations, albeit at the expense of DSP load and processing delay.

**Conclusions**

We have experimentally demonstrated the transmission of a 1.5-Tb/s guard-banded OFDM superchannel with a record SEDP of 32,000 km·b/s/Hz for Tb/s-class superchannel transmission of >5 b/s/Hz net spectral efficiency. This demonstration is enabled by high-speed EDTM through 50-GS/s DACs and ADCs allowing for a record 233-Gb/s all-electronically generated and detected OFDM signal, decision-directed pilot-free OFDM, low-nonlinearity ULAF, Raman amplification, optimized one-step-per-span NLC, and SD-FEC.

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