3× 485-Gb/s WDM Transmission over 4800 km of ULAF and 12× 100-GHz WSSs Using CO-OFDM and Single Coherent Detection with 80-GS/s ADCs

Xiang Liu[1], S. Chandrasekhar[1], P. J. Winzer[1], B. Zhu[2], D. W. Peckham[2], S. Draving[2], J. Evangelista[3], N. Hoffman[3], C. J. Youn[4], Y. H. Kwon[4], and E. S. Nam[4]

1: Bell Labs, Alcatel-Lucent, 791 Holmdel-Keyport Road, Holmdel, NJ 07733, USA
2: OFS Labs, 19 Schoolhouse Rd, Somerset, NJ, 08873, USA
3: Agilent Technologies, 5301 Stevens Creek Blvd, Santa Clara, CA 95051, USA
4: Electronics and Telecommunications Research Institute (ETRI), 138 Gajeongno, Yuseong-gu, Daejeon, 305-700, Korea
xiang.liu@alcatel-lucent.com

Abstract: We demonstrate WDM transmission of three 485-Gb/s CO-OFDM channels with 16-QAM subcarrier-modulation, each received by a single coherent detection step. Transmission over 48 100-km ULAF spans and 12 wavelength-selective-switches with 4-b/s/Hz net spectral-efficiency is achieved.

OCIS: (060.1660) Coherent communications; (060.5060) Phase modulation; (060.2330) Fiber optics communication.

1. Introduction

High-speed optical transmission with per-channel data rates beyond 100 Gb/s is being actively researched for future optical transport systems [1-3]. It is important to achieve high spectral efficiency (SE) when scaling up the per-channel bit rate in order to increase the overall system capacity. It is also important to achieve a reasonably long transmission distance in order to reduce the overall system cost. Higher-order modulation formats such as 16-QAM [4], 36-QAM [5], and 64-QAM [6] were recently used to increase SE. A 448-Gb/s reduced-guard-interval (RGI) CO-OFDM signal was transmitted over 2000 km of ultra-large-area fiber (ULAF) with five passes through an 80-GHz-grid wavelength-selective switch (WSS) [7], achieving a spectral-efficiency-distance-product (SEDP) of ~10,000 km-b/s/Hz after removing 7% overhead for forward error correction (FEC). To further increase the SEDP for 400-Gb/s transmission, FEC based on soft decision is regarded as a key enabler [8,9]. Recently, a practically implementable soft-decision FEC for digital coherent-detection systems has been demonstrated [10], offering a net coding gain (NCG) of 10.8 dB at an output bit error ratio (BER) of 10^{-15}, corresponding to an input Q^2-factor threshold of 6.4 dB (or an input BER of $\sim 1.84\times10^{-2}$) under the additive white Gaussian noise (AWGN) assumption. The needed FEC overhead is 20.5%, imposing a higher bandwidth requirement than conventional 7%-overhead FEC, especially on the analog-to-digital converter (ADC) used in the receiver front-end. Recently, a single coherent receiver front-end equipped with four 80-Gsamples/s (GS/s) ADCs having an RF bandwidth of 32.5 GHz was used to receive a record data rate of 606 Gb/s with a transmission distance of 1600 km [11]. Here, we report on the generation of a 485-Gb/s RGI-CO-OFDM signal, allowing for 21% overhead for FEC at an information bit rate of 400 Gb/s, and its detection using a single coherent detection step with four 80-GS/s ADCs. We further transmit three 485-Gb/s WDM channels over 4800 km of ULAF and twelve 100-GHz-grid WSSs, achieving a SEDP of 19,200 km-b/s/Hz, which essentially doubles the previous record [7] on 400^{+}Gb/s transmission with ≥4 b/s/Hz net SE.

2. Experimental Setup

Figure 1 shows the schematic of the experimental setup. At the transmitter, the outputs of three 100-GHz spaced external cavity lasers (ECLs), each having 100-kHz linewidth, were combined by an optical coupler (OC) before being modulated by an I/Q modulator to form three RGI-CO-OFDM signals. The generation of RGI-CO-OFDM

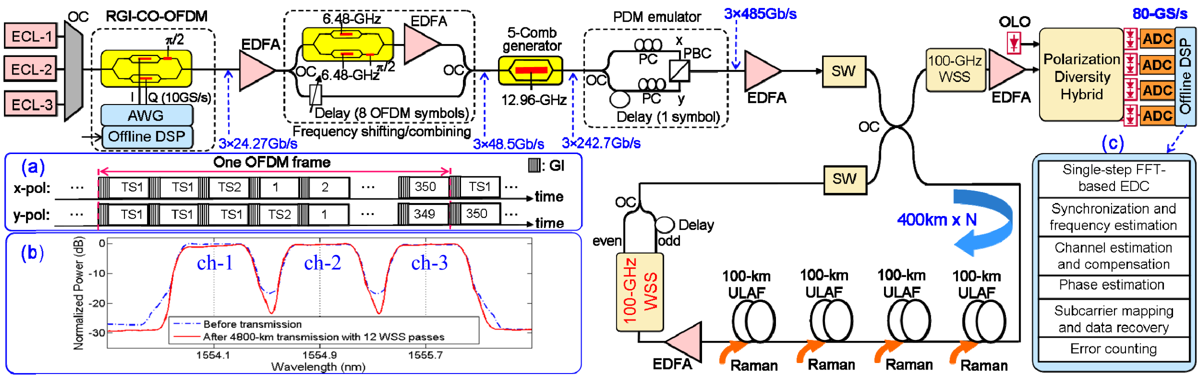

Fig. 1. Schematic of the experimental setup. Insets: (a) OFDM frame structure; (b) Optical spectra of three 485-Gb/s WDM channels before and after 4800-km transmission; (c) Block diagram of the receiver offline DSP.

is similar to that described in [7]. Offline digital signal processing (DSP) was first performed to generate an OFDM waveform, which was then stored in an arbitrary waveform generator (AWG) equipped with two 10-GS/s digital-to-analog converters (DACs). In the offline DSP, a data stream consisting of a pseudo-random bit sequence (PRBS) of length 2^{15}-1 was mapped onto 81 16-QAM subcarriers (SCs), which, together with one pilot SC, one unfilled (i.e., zero-power) DC SC, and 45 unfilled edge SCs, were converted to the time domain via an IFFT of size 128. A guard-interval (GI) of length 4 samples (or 400 ps) was used to accommodate the inter-symbol-interference induced by transmitter bandwidth limitations and dynamic effects such as fiber PMD, while static fiber chromatic dispersion (CD) was compensated at the receiver [7]. The OFDM frame structure is shown as inset (a) in Fig. 1. Four training symbols (TSs) with either even subcarriers or odd subcarriers filled [12] were inserted after every 350 payload symbols to facilitate frame synchronization, frequency estimation, and channel estimation. The payload data rate is thus 350/(350+4)×81/(128+4)×10×4=24.27Gb/s, occupying an optical spectral bandwidth of 6.48 GHz (=83/128x10G). The signals were split into two copies, one being frequency shifted by exactly 6.48 GHz through another I/Q modulator configured as a frequency shifter [7], and the other being delayed by 8 OFDM symbol periods relative to the first copy, before being seamlessly recombined to form three 48.5-Gb/s signals each consisting of two decorrelated bands. The signals were further expanded *seamlessly* to 242.7 Gb/s each with negligible crosstalk among them by using a 5-comb generator, which was based on a Mach-Zehnder modulator driven by a 12.96-GHz sinusoidal wave. Polarization-division multiplexing (PDM) with one OFDM symbol delay between the two polarizations doubled the data rate of each channel to 485 Gb/s. The WDM channels were launched into a transmission loop similar to that used in [7]. It consisted of four Raman-amplified 100-km ULAF spans having low loss (0.185 dB/km) and low nonlinearity (0.81 $W^{-1}km^{-1}$). To assess the signal performance in optically routed networks with ROADMs, we used a 100-GHz WSS in the loop to separate and recombine the even and odd channels. For each WSS passband, the 0.1-dB and 35-dB bandwidth were ~72 GHz and ~125 GHz, respectively. The optical spectra of the three WDM channels, measured by an optical spectrum analyzer with 0.1-nm resolution before and after 4800-km transmission are shown as inset (b) in Fig. 1. Evidently, no optical filtering induced spectral clipping is observed, even after 12 WSS passes.

At the receiver, each WDM channel was sequentially filtered out by a second 100-GHz WSS for performance evaluation. An optical local oscillator (OLO) was tuned to the center frequency of the channel under test. With the use of four 80-GS/s ADCs with 32.5-GHz RF bandwidth, each 485-Gb/s signal with an optical bandwidth of 64.8 GHz can be completely sampled through a single coherent detection, without having to resort to banded detection [7]. Each 80-GS/s ADC consists of a 1:8 sampler with 32.5-GHz bandwidth followed by four synchronized 20-GS/s ADCs. In addition to its wide bandwidth, each ADC has an effective number of bits of >5.5 up to 32.5 GHz. The digitized waveforms were processed offline. The DSP blocks are shown in inset (c) of Fig. 1, and are similar to those described in [7].

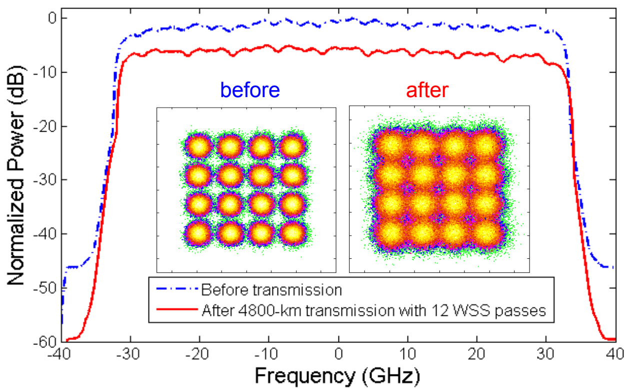

Fig. 2. Center 485-Gb/s channel spectra (with 1-GHz resolution) recovered from a single 80-GS/s ADC sampling. Inset: Typical recovered SC signal constellations before and after 4800-km transmission.

3. Experimental Results

Figure 2 shows the signal spectra of the center channel recovered from a single 80-GS/s ADC sampling. The spectrum after transmission is shifted down by 5 dB for easier comparison. The signal spectra clearly show that the 80-GS/s ADCs have a fairly flat frequency response up to 32.5 GHz. Typical recovered SC constellations before and after transmission are shown as left and right insets, respectively.

Figure 3(a) shows the BER of the center channel (obtained after processing 2.3 million bits) as a function of the optical signal-to-noise ratio (OSNR, 0.1-nm noise bandwidth; both noise polarizations). At the threshold Q^2 of 6.4 dB [10], the required OSNR is 22.2 dB, which is ~3 dB from the theoretical limit. Remarkably, a reduction in FEC Q^2–threshold of 2.1 dB provides an OSNR margin of 4.1 dB, underscoring the benefit of

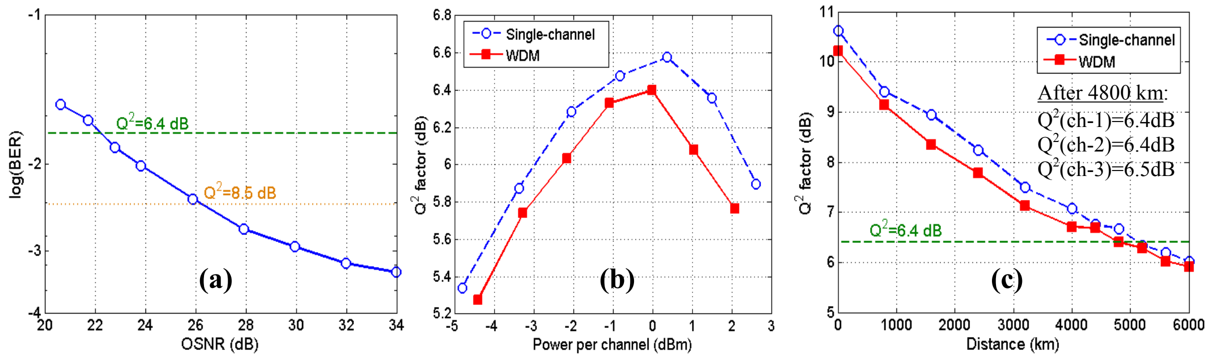

Fig. 3. (a) Measured back-to-back BER of a 485-Gb/s RGI-CO-OFDM signal as a function of the received OSNR; (b) Measured Q^2 factor of the center WDM channel after 4800-km transmission as a function of signal power; (c) Measured Q^2 factor of the center WDM channel versus transmission distance (OSNR=25 dB at 4800 km).

high-coding-gain FEC. Fig. 3(b) shows the measured Q^2 factor (derived from BER) after 4800-km transmission as a function of the signal launch power. The optimal signal launch power per channel is found to be 0.4 dBm for single-channel transmission, and 0 dBm for WDM transmission. Also remarkably, the nonlinear tolerance at the soft-decision FEC threshold, defined as the signal launch power multiplied by the number of spans, is ~3 dB higher than that measured previously assuming 7% hard-decision FEC [7], further underscoring the benefit of soft-decision FEC. Fig. 3(c) shows the Q^2 factor of the center channel as a function of transmission distance at the optimum signal powers for both the single-channel and WDM transmission cases. The WDM transmission performance is only slightly worse than the single-channel transmission, mostly due to the OSNR degradation at the transmitter when more channels are present. We also verified that signal Q^2 factors exceeding/meeting the FEC threshold were obtained up to 4800 km and 12 WSS passes for all three WDM channels.

Referring back to the soft-decision FEC performance, it is important to not just look at pre-FEC error rates (as is permissible for hard-decision FEC if errors are uncorrelated) but to also investigate the probability density function (pdf) of the signal after transmission to see if the noise distribution is, in fact, Gaussian, as the FEC NCG is derived using the AWGN assumption [8-10]. Fig. 4(a) shows the pdf of the I and Q components of both polarizations of the center channel after 4800-km transmission at the optimal signal power, which closely follows the Gaussian distribution. In addition, careful analysis of the pdf's for all 16 constellation points showed that all pdfs are identical and individually obey circularly symmetric complex Gaussian statistics. Finally, Fig. 4(b) shows the statistics of error burst lengths. The measured burst error probability decreases exponentially with the increase of burst length, as expected for uncorrelated error events, indicating that the FEC can be effective in the nonlinear transmission regime under our experimental conditions.

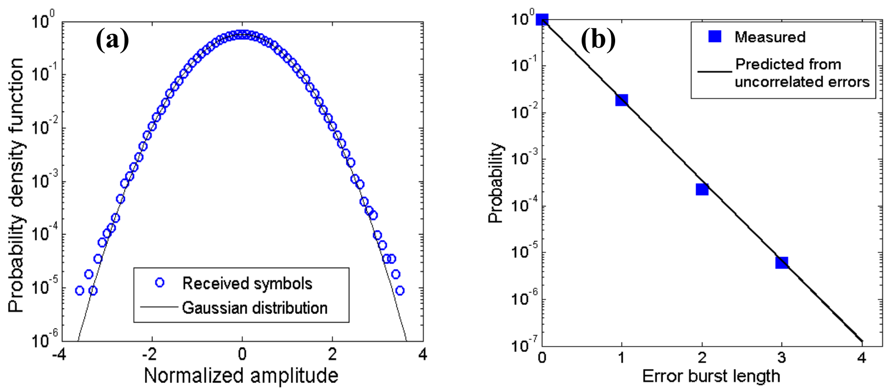

Fig. 4. (a) Probability density function of the signal distortion and (b) error burst length statistics after 4800-km transmission.

4. Conclusion

We have demonstrated a SEDP of 19,200 km-b/s/Hz for 400⁺Gb/s transmission with 4-b/s/Hz SE in optically routed long-haul WDM transmission, using 80-GS/s ADC enabled single coherent detection for each channel.
This work was partially supported by the IT R&D Program of MKE/KEIT (KI002037), Republic of Korea.

References

[1] A. D. Ellis et al., OECC'08, WeA-1.
[2] Y. Ma et al., OFC'09, PDPC1.
[3] S. Chandrasekhar et al., ECOC'09, PD2.6.
[4] A. Sano et al., OFC'10, PDPB7.
[5] X. Zhou et al., OFC'10, PDPB9.
[6] A. Sano et al., ECOC'10, PD2.4
[7] X. Liu et al., OFC'10, PDPC2.
[8] T. Mizuochi, OFC'08, OTuE5.
[9] I. B. Djordjevic et al., IEEE Photon. J. **2**, 611 (2010).
[10] Y. Miyata et al., OFC'10, OThL3.
[11] X. Liu et al., ECOC'10, PD2.6.
[12] C. J. Youn et al., ECOC'10, P4.06.