Ultra-High-Spectral-Efficiency Transmission

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Abstract: We discuss the generation, transmission, and coherent detection of 14-Gbaud polarization-division multiplexed, 16-ary quadrature-amplitude-modulation (16-QAM) signals (112-Gb/s line rate). We attain 630-km and 1020-km wavelength-division-multiplexed transmission with spectral efficiencies of 6.2 b/s/Hz and 4.1 b/s/Hz, respectively.

OCIS Codes: (060.2360) Fiber optics links and subsystems; (060.4080) Modulation; (060.4510) Optical communications

1. Introduction

To allow further scaling of wavelength-division-multiplexed (WDM) optical transport capacity beyond the current record of 32 Tb/s [1], increasing the spectral efficiency (SE) while simultaneously maintaining reasonable transmission reach is of high importance. Multi-level modulation and polarization-division-multiplexing (PDM), preferably in combination with coherent detection, are key techniques to achieve these goals. At ~100 Gb/s, the highest reported SE is now 6.2 b/s/Hz [2] using PDM and 16-ary quadrature amplitude modulation (16-QAM) of a single carrier. At 56 Gb/s, a SE of 7.0 b/s/Hz [3] has been obtained using PDM 32-QAM and orthogonal frequency-division multiplexing (OFDM). Multi-level (M-ary) modulation formats have an SE limited to $2 \log_2 M$ using PDM (i.e., 8 b/s/Hz for PDM 16-QAM). In practice, and assuming optically-routed networking with multiple add/drop multiplexers, ~50% of this value, i.e., $\log_2 M$ may be obtained. In point-to-point applications, 75% or more may be reached. Of course, the higher SE obtained using M-ary modulation comes at the expense of more stringent optical signal-to-noise-ratio (OSNR) requirements. In this paper, we report on experiments conducted at 112 Gb/s (104 Gb/s with 7% overhead for forward error correction) using PDM 16-QAM at 14 Gbaud, expanding upon our reports in Refs. 2, 4-6. We demonstrate WDM transmission on a 25-GHz grid (SE of 4.1 b/s/Hz) without requiring an optical interleaver or other optical filtering to combine the channels, and transmission on a 16.7-GHz grid using an optical interleaver, which yielded the record SE of 6.2 b/s/Hz mentioned above.

2. PDM 16-QAM Transmitter and Coherent Receiver

The setup of our 16-QAM transmitter is shown in Fig. 1. First, four copies of a true 14-Gb/s binary pseudo-random bit sequence (PRBS) of length $2^{15}-1$ are generated and amplified using high-speed electrical driver amplifiers. Although these signals are still binary, signal degradations such as reduced rise times or overshoots have to be avoided in order to keep impairments of the generated four-level signal to a minimum. For each quadrature, and after electrical amplification, the PRBS is combined with a multiple-bit (12 and 18 bits, respectively) delay-decorrelated and 6-dB attenuated version of its logic conjugate to yield the four-level signal shown in the inset of Fig. 1. The two four-level signals are decorrelated by approximately half the pattern length. The peak-to-peak voltage of the four-level signals is approximately 3.5 V. The drive signals are low-pass filtered (LPF) with 11-GHz Gaussian low-pass filters to electrically suppress modulation sidelobes before being applied to an integrated $LiNbO_3$ double-nested Mach-Zehnder (I/Q) modulator. The 16-QAM optical intensity eye diagram with its three intensity levels corresponding to the three rings that make up a square 16-QAM constellation is also shown in Fig. 1.

Our intradyne receiver is shown in Fig. 2. The signal is combined with an external cavity laser (ECL) local

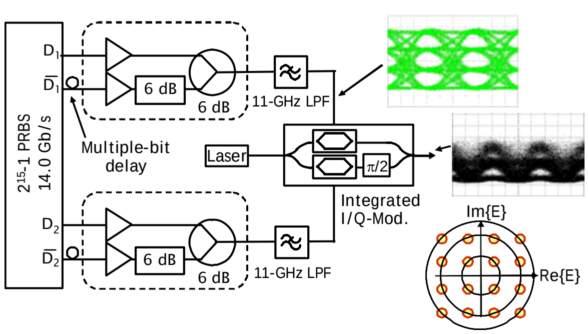

Fig. 1: Setup of the 16-QAM transmitter.

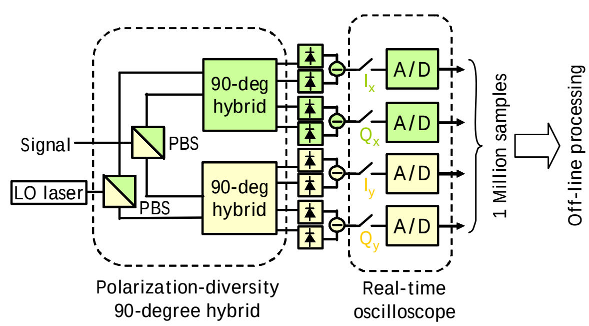

Fig. 2: Setup of the polarization-diversity coherent receiver.

oscillator (LO) in a polarization-diversity 90-degree optical hybrid. The LO is tuned to within ±20 MHz of the received-signal center frequency for reliable locking of the underlying blind algorithms. The four pairs of balanced outputs from the hybrid are sampled and asynchronously digitized at 50 GSamples/s using a commercial real-time oscilloscope with nominal 8-bit analog-to-digital (A/D) resolution and a frequency-dependent effective number of bits (ENoB) between 4 and 5. Computer simulations confirm that an ENoB greater than 4 is needed to avoid penalties in excess of 1 dB. All results shown here are based on offline processing of 10^6 samples per polarization and quadrature, corresponding to ~250,000 symbols (~2 million bits). After digital compensation of optical front-end errors (sampling skews and hybrid phase errors), perfectly rectangular digital anti-aliasing filtering is performed, and the streams are down-sampled to 28 GSamples/s (2x oversampling at 1/T = 14 Gbaud). The synchronous clock is recovered from the pronounced 14-GHz tone in the signal's power spectrum after applying FFT-based bulk chromatic dispersion (CD) compensation. The original *x* and *y* polarizations of the transmit signal are recovered using an adaptive butterfly FIR filter structure with transfer functions H_{xx}, H_{xy}, H_{yx}, and H_{yy}, each with 16 T/2-spaced taps. Filter pre-convergence is achieved with the constant modulus algorithm (CMA), followed by maximum-likelihood frequency and phase-angle estimation [6]. Final filter adaptation and phase tracking are done using a decision-directed algorithm, interleaved with a decision-directed frequency and phase tracking loop.

3. Transmission

For our WDM experiments we use the experimental setup shown in Fig. 3. Ten lasers are operated on the desired WDM grid in the C band (193.325 – 193.550 THz for experiments on a 25-GHz grid and 193.35 THz – 193.50 THz for a 16.7-GHz grid). Of these, 9 are distributed-feedback (DFB) lasers, while a tunable ECL with a 3-dB linewidth of ~100 kHz is used for the respective channel under test (computer simulations show negligible performance degradation for this linewidth). We employ two 16-QAM transmitters of the type shown in Fig. 1, one for the set of 'even' and one for the set of 'odd' WDM channels. Odd and even channels are amplified using erbium-doped fiber amplifiers (EDFAs) and combined by a simple 3-dB coupler for 25-GHz channel spacing (enabled by the electronic waveform shaping through electrical low-pass filtering of the drive signal) or a 16.7GHz/33.4GHz custom-designed silica-on-silicon optical interleaver [7] for 16.7-GHz channel spacing. After combining, the WDM channels are polarization-multiplexed by splitting them into two paths and recombining them in a polarization beamsplitter

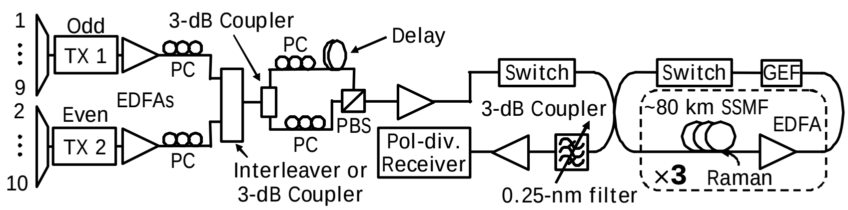

Fig. 3: Experimental setup for WDM transmission. GEF: Gain-equalizing filter.

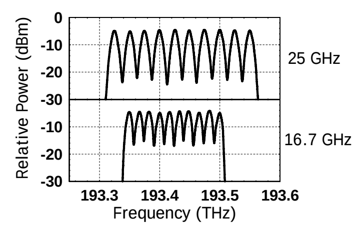

Fig. 4: Launch spectra (18-pm resolution).

(PBS), using manual polarization controllers (PCs) and a relative decorrelation delay of ~20 ns (280 symbols). Transmitted spectra at 25-GHz and 16.7-GHz channel spacing (18-pm resolution) are shown in Fig. 4.

Transmission is performed in a recirculating loop that contains four ~80-km spans of SSMF (total loop length of 315 km). The loss of the spans ranges from 16 dB to 17 dB. Span amplification is provided by backward Raman pumping (net gain of 10-12 dB) and EDFA repeaters with approximately 5-dB noise figures. No dispersion-compensating fiber is used, and all CD is digitally compensated within the coherent receiver. The total power launched into each span is +3 dBm (-7 dBm/channel), which was found to be optimum. At the receiver, the test channel, including a portion of its neighbors, was selected using a 0.25-nm-bandwidth optical filter, amplified, and combined with the LO in a coherent detection setup according to Fig. 2.

3. Results and Discussion

Figure 5 shows back-to-back bit-error-ratio (BER) measurements for the case of channels combined using a 3-dB coupler. The triangles represent the reference single-channel measurement of PDM 16-QAM, revealing a back-to-back required OSNR (noise in 0.1-nm resolution bandwidth and both polarizations) of 20.8 dB to achieve a BER of 1×10^{-3}, which is 3.8 dB off the theoretical limit (solid line) [8]. In 25-GHz WDM operation (circles), WDM crosstalk from the two nearest neighbors imposes an additional penalty of 1 dB. The penalty rises rapidly for WDM channel spacing below 20 GHz. The recovered 16-QAM signal constellations of a central WDM channel at 25-GHz spacing and 21-dB OSNR (BER of 1.3×10^{-3}) are also shown. Figure 6 shows back-to-back BER measurements for channels spaced at 16.7 GHz using the optical interleaver. The triangle curve represents the measurement of a single-channel PDM 16-QAM signal without using the interleaver, revealing a back-to-back required OSNR of 20.2 dB to achieve a BER of 1×10^{-3}. This value is 3.2 dB off the theoretical limit (solid line). When passing through the interleaver (circles), an additional penalty of 1.3 dB is incurred due to the tight optical filtering. In 16.7-GHz WDM operation (squares), crosstalk from the two nearest neighbors imposes an additional penalty of 1.5 dB. Also shown are the recovered signal constellations for a central WDM channel at 23-dB OSNR (BER of 1×10^{-3}).

For transmission with 25-GHz-spaced channels, 12-dB Raman gain was used. After 1022-km transmission (3 loop round-trips + 1 span), the average OSNR of the channels was 24 dB. The received optical spectrum (0.1-nm resolution bandwidth) and BER of each channel are shown in Fig. 7, as are the recovered signal constellations for a central channel. All BERs are below 2×10^{-3}, the threshold of enhanced FEC with 7% overhead that enables a post-FEC BER of less than 10^{-16}. For transmission with 16.7-GHz-spaced channels, the optimum Raman gain was found to be 10 dB. After 630-km transmission (2 loop round-trips), the average OSNR of the channels was 24 dB. As shown in Fig. 8, the BERs of all channels are again below 2×10^{-3}.

4. Conclusion

We have summarized a series of experiments that demonstrated the first blind intradyne detection of PDM 16-QAM signals at 112 Gb/s. We have described transmitter and receiver setups and analyzed their performance using both simulated and measured waveforms. We obtained a back-to-back required OSNR of 20.2 dB (BER=1×10^{-3}), which is 3.2-dB off the theoretical limit. In a 25-GHz-spaced 10-channel WDM environment (4.1 b/s/Hz), we demonstrated transmission over 1022 km of fiber (~80-km SSMF spans with hybrid Raman/EDFA repeaters). Electrical waveform shaping allowed us to combine the WDM channels using a simple 3-dB coupler and no optical interleaver filters. On a 16.7-GHz WDM grid (6.2 b/s/Hz) we used an optical interleaver to combine channels, and achieved 10-channel transmission over 630 km of fiber using the same line system.

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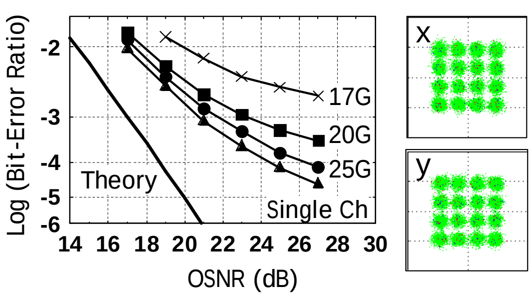

Fig.5: BER measurements for colorless (interleaver-free) WDM combination and channel spacings of 25 GHz, 20 GHz, and 17 GHz.

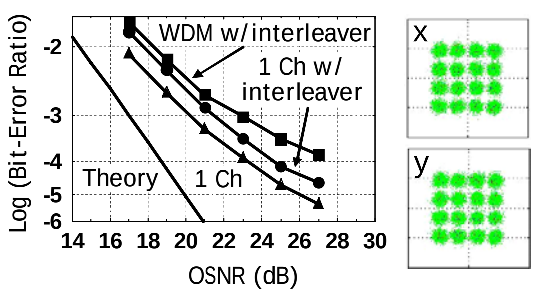

Fig. 6: BER measurements for 16.7-GHz-spaced WDM.

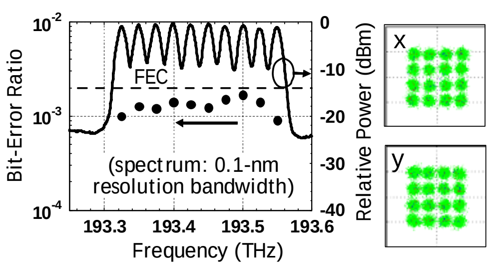

Fig. 7: BER results for 25-GHz WDM 1022-km transmission.

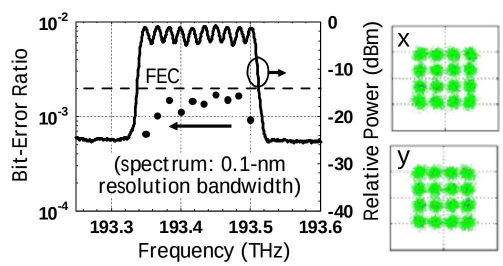

Fig. 8:BER results for 16.7-GHz WDM 630-km transmission.