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Experimental Characterization of 10 × 8 GBd DP-1024QAM Transmission with 8-bit DACs and Intradyne Detection

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Abstract *We experimentally investigate the transmission of 10 × 8 GBd DP-1024QAM over full Raman amplified low-loss fiber spans. For multicarrier systems using 8-bit DACs, a record achievable information rate of 15.7 bit/symbol is observed after 200 km using standard intradyne detection.*

Introduction

Spectrally-efficient optical transmission enabled by high-order modulation formats can provide high throughput with flexible rates for short and metro-haul networks. The scaling of achievable rates with high-order M-ary quadrature amplitude modulation (M-QAM) formats requires increased effective received signal-to-noise ratio (SNR) for successful detection and decoding. The effective received SNR is ultimately bounded by the effective number of bits (ENOB) of the digital-to-analog converters (DACs) and the analog-to-digital converters (ADCs). Moreover, the effective received SNR may be decreased due to implementation penalties related to sub-optimal equalization or sub-optimal carrier phase recovery. Typically, implementation penalties increase with the order of the modulation format. Nevertheless, the use of constellations with large cardinalities is a promising option for highly spectrally-efficient transmission over short and metro haul distances, where the performance is dominated by the transceiver noise. A number of experimental demonstrations of single-carrier transmission with high-order M-QAM ($M \geq 1024$) have been shown[1–4]. However, the total information rates achieved in those demonstrations were limited to less than 70 Gb/s, due to single channel operation and relatively low symbol rate. Recently, a multicarrier transmission of 10 × 3 GBd DP-4096QAM was demonstrated[5], achieving 545 Gb/s of throughput over 50 km of fiber within an optical bandwidth of 32 GHz. Nevertheless, all those experiments were performed using DACs with more than 10-bit resolution limiting their symbol rates per carrier to ≈3 GBd, since such devices can provide relatively small analog bandwidth and sampling rates when compared to commercial 8-bit DACs (65 GS/s, 20 GHz).

In this paper, we experimentally investigate the generation and transmission of a 10 × 8 GBd DP-1024QAM multicarrier system. The multicarrier system employs 8-bit DACs and a standard intradyne coherent receiver, with a potential to reach an aggregated information throughput above 1 Tb/s after 200 km of full-Raman amplified fiber transmission. The results shown are achieved with the use of probabilistic shaping in combination with a stable low-linewidth comb source and optimized pilot-based equalization and pilot-assisted carrier phase recovery. We further analyze the performance of the system as a function of the overhead of pilot symbols used for equalization and carrier phase recovery.

Experimental setup and DSP

The experimental setup is shown in Fig.1. The ten optical subcarriers with 8.5 GHz spacing are generated as two separate frequency-locked optical frequency combs with 17 GHz free spectral range and 8.5 GHz frequency offset. The comb for the even subcarriers is generated by direct phase modulation of a seed laser (NKT Koheras Basik fiber laser) using a 17 GHz sinusoidal driving signal. The comb for the odd subcarriers is based on a frequency shift of the seed laser by 8.5 GHz carrier-suppressed amplitude modulation. The +8.5 GHz tone is used as seed for an injection locked laser, isolating that line and boosting its power. The output of the injection locking laser (ILL) is phase modulated in the same manner as the other comb, to generate the frequency-locked comb with an 8.5 GHz offset. Therefore, the final multicarrier system comprises ten carriers modulated at 8 GBd with a grid spacing of 8.5 GHz. The DP-1024QAM transmitted symbols are generated by LDPC-encoded (DVB-S.2 standardized FEC) pseudo random bit sequences. For the uniformly distributed 1024QAM, the encoded bits are interleaved and Gray mapped into QAM symbols. For the probabilistically shaped 1024QAM, the QAM symbols are generated by the combination of two 32-ary probabilistic amplitude shaped sequences obtained by using a distribution matcher (DM)[6]. Two decorrelated sequences of four LDPC blocks are loaded in the arbitrary waveform generator (AWG). The signal is digitally pulse shaped with a root-raised cosine (RRC) filter with 401 taps and roll-off factor of 0.02. A linear pre-emphasis is applied to compensate for the combined frequency response of transmitter and receiver. Four RF filters with 4.9 GHz of 3 dB bandwidth are connected to the AWG outputs to minimize inter-carrier crosstalk. After amplification, each baseband signal drives one of two in-phase/quadrature (IQ) modulators.

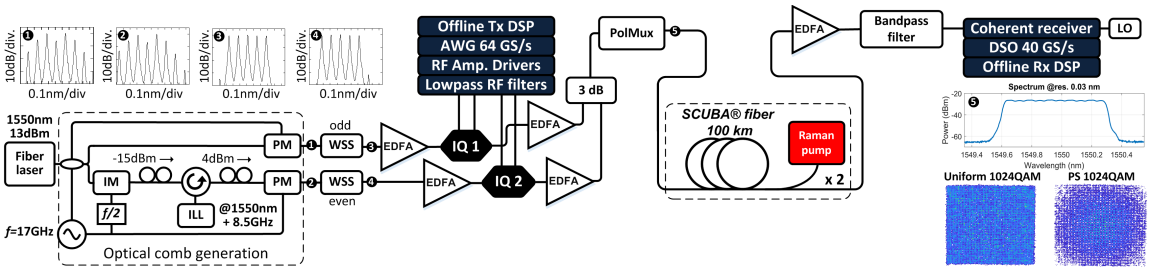

Figure 1 Experimental setup detailing the transmitter, the fiber link, the coherent receiver and the offline digital signal processing.

The signals are combined to create the even-odd ten carrier signal and polarization multiplexing is emulated.

The multicarrier signal propagates in a fiber link composed of two 100 km spans of ultra-large-area low-loss fiber (OFS TeraWave®, SCUBA Ocean Fiber) with average loss and dispersion coefficients of 0.155 dB/km and 22 ps/nm/km, respectively, at 1550 nm. All the span losses are compensated by distributed Raman amplification (backward pumping, 1455 nm, 1.1 W/span). One erbium-doped fiber amplifier (EDFA) is added as a pre-amplifier for the coherent receiver. At the receiver, intradyne coherent detection is performed using a second independent fiber laser as local oscillator and the signal is sampled at 40 GS/s. The bandwidth of the oscilloscope is fixed to 5 GHz. The offline DSP processing is composed of a receiver front-end compensation stage, low-pass filtering, chromatic dispersion compensation, resampling to 2 samples/symbol, clock recovery, pilot-based $T_s/2$-fractionally spaced radius-directed adaptive equalization (45 taps, 5% pilot-symbols), pilot-aided carrier phase recovery, and a post decision-directed recursive least square equalizer with 7-taps. Here, for simplicity and differently from[8], the equalizer taps are kept static in between pilot-based adaptations. In back-to-back (B2B) and at maximum optical SNR (OSNR) of 43 dB (per 0.1 nm), the average effective received SNR per carrier saturates at ≈25 dB. The mutual information (MI) is used as figure of merit to estimate the achievable rate of the system under the assumption of a memoryless auxiliary channel impaired by complex-valued circularly symmetric additive white Gaussian noise (AWGN).

Transmitter/receiver characterization

We first evaluate the performance of the transmitter and receiver in different scenarios to estimate the implementation penalties of the electrical and optical components, and the sub-optimal DSP. The results are summarized in Tab. 1. Unless stated otherwise, all the measured effective SNR results are obtained employing full data-aided DSP.

In the first column of Tab. 1 it is shown the bound on the maximum achievable effective received SNR, assumed to be the signal quality at the DACs' outputs and given by $\text{SNR}_{DAC} \approx 6.02\times\text{ENOB}+1.76$, with the ENOB of 5.5 bits taken from the DACs' specification. In electrical back-to-back (B2B) configuration the maximum measured effective SNR at the receiver is 32 dB representing the DAC+ADC hardware performance. A penalty of 3 dB is observed after adding RF amplifiers to the DACs outputs, reducing the maximum effective SNR to 29 dB. At maximum OSNR, the same 29 dB is observed in B2B for a single-carrier 8 GBd, revealing no extra penalty from optical components, (i.e. the optical modulators, EDFAs and coherent optical receiver, see Fig. 1). In the multicarrier configuration, each IQ modulator receives five carriers at the same total input power of the single carrier configuration, thus reducing the maximum output power per carrier. Additionally, inter-carrier crosstalk appears after the combination of even and odd carriers. Both effects lead to a 3 dB of effective received SNR penalty for a full data-aided DSP. Finally, using 5% pilot-aided DSP an additional penalty of 0.5 dB is found in comparison with the full data-aided DSP performance.

Transmission performance

We investigate the transmission performance over a straight line 200 km full Raman amplified link. We use "symbol" to refer to the four-dimensional constellation symbol composed of both polarizations.

In Fig. 2 (a), the achieved MI per transmitted carrier are depicted for B2B at maximum OSNR and after 200 km of straight line transmission. In B2B and for uniform DP-1024QAM the average MI is 15.9 bit/symbol, whereas for the shaped 1024QAM it is 16.8 bit/symbol. Therefore, in B2B at maximum OSNR, an average shaping gain of 0.9 bit/symbol is observed. The fiber transmission results are obtained for the optimal launch power of the multicarrier signal, found to be -7.5 dBm per carrier. After 200 km of straight transmission, the average effective received SNR reduces by 1.0 dB and MI penalties of 0.9 and 1.0 bit/symbol are observed for the uniform and the shaped 1024QAM, respectively. Note that on the AWGN channel, 1 dB SNR reduction leads to smaller penalties (3 dB per 1 bit is the rule of

Tab. 1: Summary of transceiver characterization results, including maximum theoretical reference. The experimental results refer to signal generation at 8 GBd.

Max. theoretical SNR (ENOB 5.5)	Max. measured effective electrical SNR (DAC + ADC)	Max. measured effective electrical SNR (DAC + RF amp. + ADC)	Max. measured effective SNR single-carrier B2B (full data-aided DSP)	Max. measured effective SNR multicarrier B2B (full data-aided DSP)	Max. measured effective SNR multicarrier B2B (5% pilot-aided DSP)
34.9 dB	**32 dB**	**29 dB**	**29 dB**	**26 dB**	**25.5 dB**

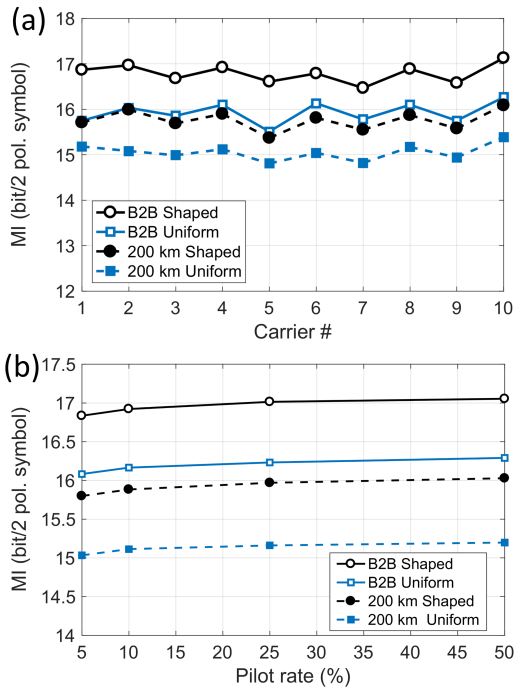

Figure 2 (a) B2B and straight line transmission performance results for all 10 carriers; (b) Variation of the MI measured for carrier #6 as a function of the rate of pilot symbols used for equalization and carrier phase recovery.

thumb). The extra penalties observed are most likely due to nonlinearities or sub-optimal DSP. Hence, the shaped constellations achieve on average 15.7 bit/symbol, whereas the uniform ones achieve 15.0 bit/symbol. The shaping gain is then reduced to 0.70 bit/symbol. The variations of MI between carriers is mostly due to imperfect equalization of the spectrum (i.e., variations in OSNR within 0.5 dB) after modulation and amplification.

In Fig. 2 (b), the performance dependence on the pilot overhead for carrier # 6 is shown. It can be noted that the performance of the pilot-aided DSP is virtually independent of the input distribution since, moving from 50 to 5% pilot overhead the same penalties are observed for both uniform and shaped constellations. Moreover, both in B2B and after fiber transmission, the penalties observed by lowering the pilot overhead to 5% are ≈0.2 bit/symbol, corresponding to a loss in effective received SNR of ≈0.4 dB.

To verify the performance of the FEC, we have used an LDPC code with rate 4/5 (25% overhead) plus 3.75/4 rate for the DM, therefore providing 15 bit/symbol for the probabilistic shaped 1024QAM. For this rate, a threshold of ≈ 24.8 dB of effective received SNR was found to obtain error-free decoding, assuming a potential use of an outer hard FEC of rate 0.992 to remove a $< 10^{-6}$ error floor of the LDPC code. Therefore, post-FEC error free performance could be achieved for the shaped constellation in B2B. For the uniform 1024QAM we used an LDPC code with rate 3/4 (33% overhead), 15 bit/symbol, that requires an effective received SNR slightly higher than 25 dB. Thus, even in B2B, it does not achieve error-free performance in the multicarrier configuration. Further rate adaptation is required to approach the MI values measured after fiber transmission. For comparison, in[7] a 5 × 16 GBd DP-256QAM multicarrier system was generated, achieving a MI ≈ 14.5 bit/symbol in B2B with the aid of probabilistic constellation shaping. Therefore, under similar conditions, the results in this paper demonstrate that higher MI values (≈1.0 bit/symbol higher) can still be obtained using 8-bit DACs.

Conclusion

We have investigated the transmission of 10 × 8 GBd DP-1024QAM using 8-bit (ENOB 5.5 bits) DACs and standard intradyne coherent detection. An average MI performance of 15.7 bit/symbol after 200 km transmission is demonstrated approaching the limits set by implementation penalties of commercial optoelectronics.

Acknowledgements

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