A Simplified Dual-Carrier DP-64QAM 1 Tb/s Transceiver

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Abstract: A 1 Tb/s net bitrate transceiver using a low complexity dual-carrier architecture with free running lasers and DP-64QAM, enabled by pilot-aided DSP and low-rate LDPC, is shown to achieve transmission over 400 km with 100 km amplifier spacing.

OCIS codes: 060.1660 Coherent communications, 060.4080 Modulation

1. Introduction

While recent research has led to several demonstrations of 1Tb/s optical communications systems utilizing a single receiver [1–5], typically those demonstrations have relied upon transmitter structures which would prove highly challenging for implementation in commercial products. These transmitter structures have variously used optical frequency combs [1–3], nonlinear optical processing [4] or custom high-frequency signal converters in InP [5]. Previous demonstrations of 1Tb/s transceivers have also relied on carrier phase estimation (CPE) algorithms that have high complexity [1, 2, 5], or cannot be implemented in parallel [3].

In this paper we describe a transceiver which has both optical and electrical transmitter hardware suitable for implementation in commercial systems. A pair of $LiNbO_3$ I/Q modulators were used, similar to those now commercially available in a single package for dual carrier systems, along with a pair of nominal 100 kHz linewidth lasers to generate the optical subcarriers. Conventional digital-to-analog converters (DACs) in CMOS were used. Two 60 GBd subchannels of dual-polarization 64-ary quadrature amplitude modulation (DP-64QAM) were spaced at 62 GHz, optically multiplexed, and detected with a single digital coherent optical receiver with 63 GHz of bandwidth, before being processed offline. Reduced complexity pilot-aided CPE enabled accurate tracking of carrier phase with only 1.43% pilot symbols. Transmission was demonstrated over 400 km of Corning® Vascade® EX2000 fiber using 100 km spans.

2. Experimental Setup

A schematic of the dual-carrier 60 GBd DP-64QAM transmitter setup is shown in Fig. 1. A digital root-raised cosine (RRC) filter with 0.1% roll-off was used to spectrally shape 64-QAM signals, and pre-emphasis was applied to compensate for the frequency response of the transmitter components. Since the modulator roll-off was reasonably slow, it was possible to achieve an SNR ceiling of approximately 16.5 dB with careful pre-emphasis. The signals were transmitted by four synchronized 92 GS/s DACs. The RF signals were then amplified by 30 GHz bandwidth modulator drivers. Two external cavity lasers (ECLs) with 100 kHz nominal linewidth and 62 GHz spacing were used as carriers for two independent I/Q modulators, with 3 dB bandwidth of approximately 25 GHz. The combined attenuation of the DAC, RF drivers and modulators was approximately 7.3 dB at 30 GHz. The wavelength channels were combined, and polarization multiplexing emulated with an interferometer with 14.1 ns delay between arms. Spectrally shaped amplified spontaneous emission (SS-ASE) noise was used as an ultra-broadband source to emulate fully-loaded C-band transmission [6].The SS-ASE source had a bandwidth of 4.5 THz and a notch centered at 1550 nm with a bandwidth of 140 GHz was carved out to accommodate the channel of interest (see inset Fig. 1). A 9 GHz guard-band on each side of the 122 GHz dual-carrier signal was used to minimize linear crosstalk induced penalties [6].

For transmission, a recirculating loop was used, with a loop-synchronous polarization scrambler (PS), and a single span of 101.39 km of Vascade EX2000 fiber with a total loss of 16.2 dB. This fiber has both extremely low loss, and a silica core with large effective area. The span was followed by an EDFA with 18 dBm output power and 5 dB noise figure to overcome fiber attenuation. A WSS used as a dynamic gain flattening filter to compensate gain tilt from the optical amplifiers, followed by another EDFA in order to overcome loop component losses. A third ECL with 16 dBm

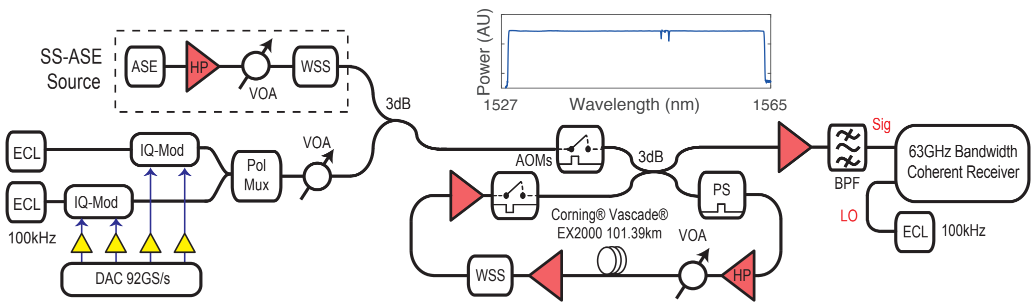


Fig. 1. Experimental setup used in this work. Inset: spectrum for spectrally shaped ASE.

output power and 100 kHz nominal linewidth was used as local oscillator in the optical receiver. Detection was carried out by balanced photodetectors with 70 GHz electrical bandwidth and without trans-impedance amplifiers. Finally, the received signals were captured by a real-time digital oscilloscope with an analog electrical bandwidth of 63 GHz at 160 GSa/s.

3. Receiver Digital Signal Processing

The receiver DSP was of a similar structure to that described in our previous work [2], albeit with significantly lower CPE complexity. After normalization, the signal underwent frequency domain equalization of chromatic dispersion. Coarse adaptive equalization was performed, and a 4^{th} power algorithm was used to calculate the subchannel intradyne frequency offsets. The signal was then digitally down-converted and low pass filtered with a matched RRC filter to separate each of the constituent subchannels. The receiver was first operated in training mode, to ensure accurate initial convergence of the adaptive equalizers, and to enable calculation of the set of centroids and SNR of each polarization subchannel.

Training mode: A pair of trained dual-polarization radius-directed equalizers (DP-RDE) were used to demultiplex the training sequence polarizations and compensate for filtering effects. The least mean square (LMS) update algorithm was used, with 151 taps in each of the four constituent FIR filters. Following this, carrier phase was corrected with a trained, feed-forward phase estimator. The training signal with corrected phase was then used to calculate the set of symbol centroids, and SNR for each of the polarization sub-channels.

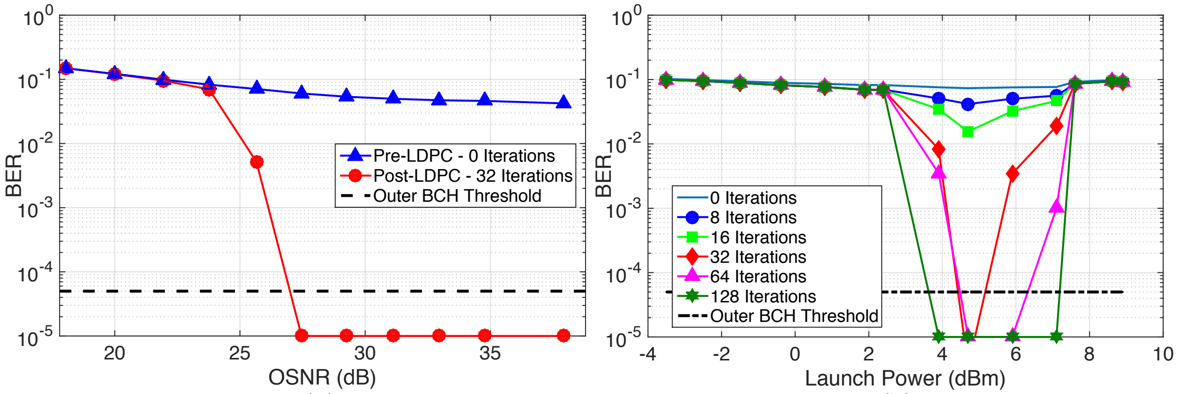
Pilot-aided mode: After initial training, the receiver was switched to pilot-aided operation. A single dual-polarization pilot occurred every 71 symbols, corresponding to a pilot overhead of 1.43%. A pair of pilot-aided DP-RDEs with LMS updating were used to equalize the signals, with the taps initialized by the training sequence. Pilot-aided carrier phase estimation was then performed on each polarization subchannel independently. Firstly, the field of seven pilots were averaged, in order to reduce the effect of additive noise on the pilot phase estimation. The averaged pilot sequence was then unwrapped, and interpolated as a piecewise linear function to provide an initial phase estimate. This phase estimate was then used to initialize a reduced complexity Expectation-Maximization (EM) algorithm [7], considering only four nearest neighbor symbol likelihoods. The EM algorithm employed the symbol constellation centroids and SNRs calculated during the training period. After two iterations of the EM algorithm, the phase was averaged by a 255 tap averaging filter, and applied to the equalized symbols. Bit-wise log-likelihood ratios (LLRs) were then calculated, again according to the symbol constellation centroids and SNRs calculated during the training period.

Forward Error Correction Coding: An inner check-concentrated, triple-variable-degree LDPC code was used, with rate 0.71 and word length of 52,800 bits. The bit LLRs were de-interleaved across all bit positions, polarizations and wavelength subchannels to ensure optimal performance. The decoder used the sum-product algorithm, with flooding decoder scheduling. The use of an outer hard-decision BCH code with rate 0.9922 was assumed, which decodes an input BER of 5×10^{-5} to an output BER of 10^{-15} or better [2]. We therefore assume that a post LDPC BER of 5×10^{-5} can be decoded to a BER of 10^{-15} or better after the BCH decoder, which was not implemented.

4. Results

BER performance before and after LDPC decoding was characterized with an ASE noise loading setup in back-to-back configuration, then with transmission over 400 km of Vascade EX2000 fiber with full C-band SS-ASE loading.

The results of the back-to-back characterization are shown in Fig. 2(a). We show total average BER before and after 32 iterations of the LDPC decoder. Note that the OSNR required for operation at a BER of 10^{-15} or better is approximately 27 dB. A measurement taken with an OSNR of 25.7 dB has a pre-LDPC decoding BER of 7×10^{-2},



(a) (b)

Fig. 2. Experimental results: (a) BER averaged over both subchannels in back-to-back configuration before and after LDPC decoding. (b) BER performance after transmission over 400 km of Vascade EX2000 fiber with full C-band ASE loading. Note that measurements exhibiting no bit errors after LDPC decoding over 3×10^6 bits per measurement are rounded up to a BER of 10^{-5}.

which is improved to a BER of 5×10^{-3} after 32 iterations of the LDPC decoder. The next measurement had an OSNR of 27.5 dB, and no errors after 32 iterations over the approximately 3×10^6 bits detected in a single capture.

The results after transmission over 400 km are shown in Fig. 2(b). We show BER before decoding, and then after 8, 16, 32, 64 and 128 iterations of the LDPC decoder. We note that while a single measurement was below the outer code threshold after 32 decoder iterations, increasing the number of iterations increased the launch power margin. The system had approximately 4 dB of launch power margin after 128 decoder iterations, with post-LDPC BER better than 5×10^{-5}, achievable between approximately 3 dBm and 7 dBm launch power.

5. Conclusions

We have proposed and demonstrated a simplified 1 Tb/s transceiver, using a dual-carrier transmitter and a single coherent optical receiver. The transmitter was implemented with commercially available components, including a CMOS DAC, a pair of $LiNbO_3$ modulators and a pair of free running lasers. Digital pre-emphasis was used at the transmitter to extend the bandwidth of the modulator, RF drivers and DAC. At the receiver, training sequences were used to ensure accurate equalizer convergence, and provide signal and noise statistics for both CPE and LDPC decoder. Low complexity, pilot-aided CPE was used with a 1.43% pilot insertion ratio, exploiting the statistics of the signal and channel. A concatenated LDPC and BCH FEC scheme was proposed, with the LDPC implemented in offline post-processing. Combined, these schemes enabled the first transmission of a dual-carrier 1 Tb/s signal using components similar to those immediately available for commercial implementation.

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