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Abstract

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Abstract *We demonstrate detection of a superchannel with net bit rate in excess of 1 Tb/s with a single coherent receiver. Novel, pilot-aided equalization and carrier recovery algorithms enable detection of an* 11×10 *GBd DP-64QAM Nyquist superchannel (1.32 Tb/s gross bit rate).*

Introduction

In order to provide higher optical interface rates, recent research has focused on the expansion of both bandwidth and spectral efficiency[1,2]. While some research has focused on the slicing of the received signal in the time[3,4] or frequency[5] domains, these solutions require several parallel coherent receivers. More recently, detection of 1 Tb/s with a single coherent receiver has been demonstrated with several coherent optical carriers being used to synthesize a single-carrier dual-polarization 32-ary quadrature amplitude modulation (DP-32QAM) signal[6].

In this paper we demonstrate detection of a coherent superchannel with net bit rate in excess of 1 Tb/s with a single coherent receiver. An optical comb generator is used at the transmitter to generate a Nyquist-spaced superchannel[7], consisting of 11×10 GBd DP-64QAM. With a single coherent receiver, a gross bit rate of 1.32 Tb/s is detected. At the receiver, we use novel pilot-aided equalization and carrier recovery algorithms, which enable robust performance over subcarriers with varying signal-to-noise ratios (SNRs). We note that the novel algorithms presented in this work are of moderate complexity and suitable for parallel implementation in hardware.

Experimental setup

The setup used in this experiment is shown in Fig. 1(a). An external cavity laser (ECL) with 100 kHz linewidth was used to seed an optical comb generator (OCG), resulting in 11 subcarriers spaced at 10.01 GHz[8]. The carriers were then separated into odd and even channels by cascaded interleavers, before modulation using single polarization I/Q modulators. Two field-programmable gate arrays (FPGAs) were used to send the in-phase and quadrature components of the desired waveforms to a pair of digital-to-analog converters, operating at 20 GSa/s. The 10 GBd, 8-level signals were generated from decorrelated de Bruijn sequences of length 2^{15}, which were filtered with a root-raised-cosine (RRC) finite impulse response filter with a roll-off of 10^{-3}. After modulation and decorrelation by 17 ns in the optical domain, the odd and even channels were combined, before passive polarization multiplexing emulation (with delay of 489 symbols). The optical receiver used was a discrete micro-optic 2×8 90° hybrid with 4 unamplified, balanced photodiodes used for detection (with bandwidth 70 GHz). The local oscillator was an ECL with linewidth 100 kHz, tuned to within 100 MHz of the transmitter seed laser. The electrical signals were digitized using an oscilloscope with 160 GSa/s analog-to-digital converters and 63 GHz of bandwidth, before being processed offline using Matlab.

Receiver digital signal processing

The receiver digital signal processing (DSP) model used in this paper is shown in Fig. 1(b). After normalization and deskewing of each quadrature, the signal was digitally down-converted and low pass filtered with a matched RRC filter to separate each of the constituent subchannels, which were then processed concurrently. The receiver was first operated in training mode, to ensure highly accurate initial convergence of the adaptive equalizers, and to enable calculation of the centroid of each constellation point, before switching to pilot-aided operation.

Training mode

For each subchannel, a dual-polarization radius-directed equalizer (DP-RDE) with least mean square updating was used to equalize polarization rotations and filtering impairments, and to re-

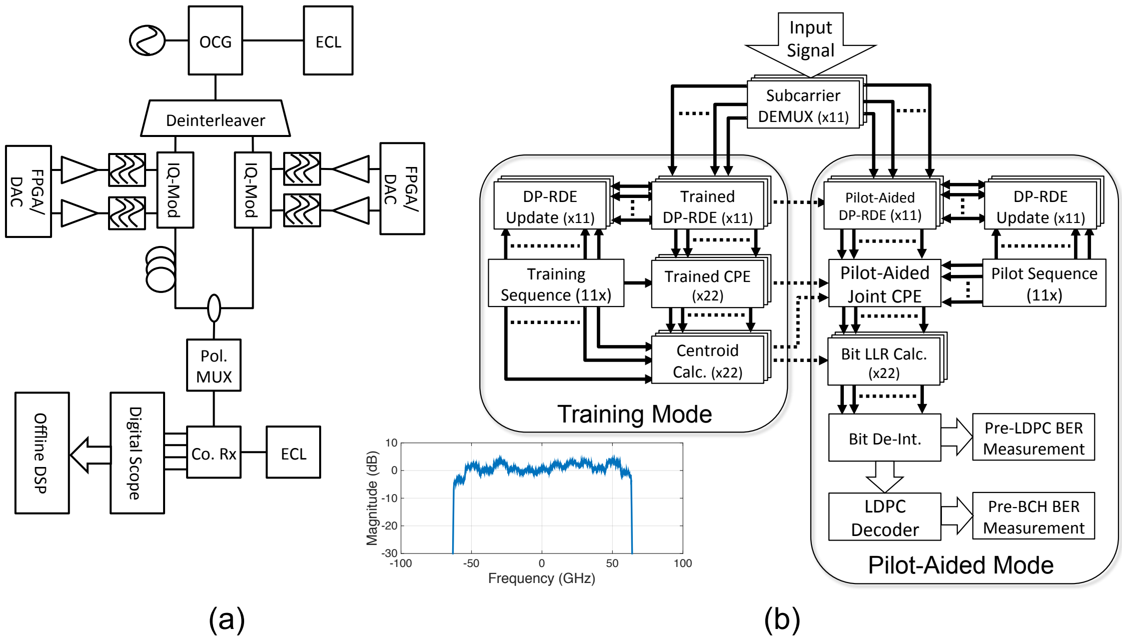

Fig. 1: (a) Experimental setup for 11 subcarrier superchannel detection with single coherent receiver. Received spectrum after quantization shown inset. (b) Receiver DSP signal flow diagram, highlighting training and pilot-aided modes of operation.

cover the timing phase. The equalizer was trained based on the radius of the symbols in the training sequence. This enabled the equalizer to achieve extremely accurate convergence before switching to pilot-aided operation. Carrier phase estimation (CPE) was performed using a data-aided feed-forward algorithm. After correcting for the phase noise on the training sequence, we were able to calculate the centroid of each of the 64 constellation points, and the SNR for each of the 22 polarization subchannels. This information was subsequently used in the pilot-aided CPE, and the calculation of bit log-likelihood ratios (LLRs).

Pilot-aided mode

After training was completed, the receiver was switched to pilot-aided mode, with a 1% pilot insertion ratio (PIR). The equalizer taps previously calculated during training mode were used as the initial state of the pilot-aided equalizers. The DP-RDE algorithm was again used, with the error calculation being performed only for the pilot symbols (rather than every symbol during training mode). Adaptation of the equalizer was performed every 10 pilot symbols, by averaging the error over a block of 10 pilots. This sub-rate adaptation enabled us to further reduce the influence of tap noise while operating with a convergence parameter of 1×10^{-4}.

Pilot-aided CPE was also performed by exploiting the 1% inserted pilots. Initial phase estimation was performed jointly for all subchannels over a block of 99 information symbols, from the two pilots on either side of the block on each of the 22 polarization subchannels (88 total pilots). These initial estimates were enhanced with the aid of a short Kalman smoother. Following this, the instantaneous phase estimates on each subchannel were enhanced by two iterations of the expectation-maximization algorithm. Finally, the resulting phase estimates in each subchannel were filtered with a moving average filter, the width of which was optimized by SNR. Bit LLR calculation was then performed on a per-polarization, per-subchannel basis, using the centroids and SNRs calculated during training (assuming additive white Gaussian noise).

We used a check-concentrated irregular low-density parity-check (LDPC) (105600,82368) code[9] with rate 0.78 for the inner code. De-interleaving was performed over all subchannels, polarizations, and time. LDPC decoding was performed with 60 iterations of the sum-product algorithm. We assume the use of an outer Bose-Chaudhuri-Hocquenghem (BCH) (30832,30592) code (rate 0.9922)[10] with minimum Hamming distance of 33. We have calculated a union (upper) bound of 10^{-15} on the BCH decoder output bit error rate (BER) given an input BER of 5×10^{-5}. Therefore, the input BER threshold for this code is at or above an input BER of 5×10^{-5}.

Results

By training all 11 of the 2×2 DP-RDE equalizers independently, we are able to achieve equalization with very low DSP penalty. We note from

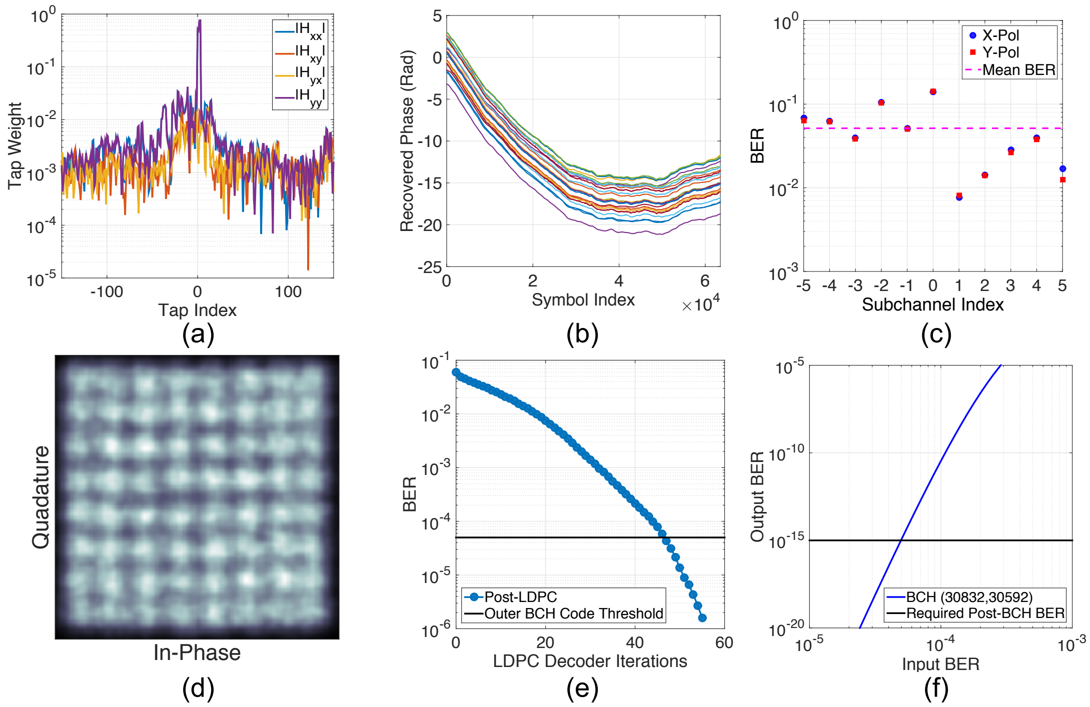

Fig. 2: (a) Absolute value of equalizer taps for the central subchannel after training period. (b) Recovered phase for the 22 joint estimates (1 per pol. subchannel). (c) BER vs channel index before LDPC decoding. (d) Constellation for subchannel 4, pol-X, exhibiting BER close to mean BER over all channels. (e) Convergence of LDPC decoder, compared with threshold for outer BCH code. (f) Union bound on outer BCH decoder performance, indicating input BER threshold at or above 5×10^{-5}.

the taps for the central subchannel (shown in Fig. 2(a)), that the impulse response of the channel is longer than may be expected, and 301 taps are required for good performance. We provide the 22 separate polarization subchannel phase estimates in Fig. 2(b). While the phases evolve in the same manner, there is an offset for each phase determined by the differences in optical path length for the interleavers and interferometers, which comprise the transmitter. From Fig. 2(c), we note that the polarization subchannel BERs range from 8×10^{-3} to 1.4×10^{-1}. We achieve good performance over all transmitted data by performing interleaving of FEC codewords over time, polarization and subchannels. Fig. 2(d) shows the constellation diagram of subchannel 4, polarization X, which exhibits performance close to the mean BER over all channels. LDPC decoder convergence is shown in Fig. 2(e), averaged over all 74 codewords detected. We note that after 47 iterations, the decoder output BER is below the outer BCH threshold, while after 55 iterations, no errors are detected over 7.8 million bits. The union bound on the performance of the outer BCH code is shown in Fig. 2(f). This indicates that the threshold for an output BER of 10^{-15} is at an input BER of 5×10^{-5} or higher.

Conclusions

We have demonstrated detection of a superchannel with a net data-rate of 1 Tb/s with a single digital coherent receiver. A Nyquist-spaced coherent superchannel, consisting of 11×10 GBd DP-64QAM was detected with a high bandwidth receiver. Novel, pilot-aided DSP algorithms of moderate complexity and suitable for hardware implementation were used, enabling robust performance over varying subchannel SNRs with 1% pilot symbols. An inner LDPC code and an outer BCH code were used, with combined overhead of 29.2%.

Acknowledgements

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References

[1] G. Raybon et al., Proc. ECOC, 2013, PD2D3.
[2] S. Beppu et al., Proc. OFC, 2014, W1A6.
[3] C. Zhang, et al., Proc. OFC, 2009, OTuG3.
[4] J.K. Fischer et al., JLT, 29, 2011, p. 378.
[5] N. Fontaine et al., Proc. ECOC, 2013, Mo3D5.
[6] R. Rios-Müller et al., Proc. OFC, 2015, Th5B1.
[7] G. Bosco et al., JLT, 29, 2011, p. 53.
[8] R. Maher et al., Nat. Sci. Rep., 5, 2015, p. 8214.
[9] T. Koike-Akino et al., Proc. OFC, 2015, W4K1.
[10] K. Sugihara et al., Proc. OFC, 2013, OM2B4.