110-Gb/s Multi-band Real-time Coherent Optical OFDM Reception after 600-km Transmission over SSMF Fiber

S. Chen, Y. Ma, and W. Shieh
Centre for Ultra-Broadband Information Networks and Victoria Research Laboratory (NICTA)
Department of Electrical and Electronic Engineering
The University of Melbourne, Melbourne, VIC 3010, Australia, e-mail: siminc@ee.unimelb.edu.au

Abstract: We demonstrate real-time reception of a 110-Gb/s multi-band OFDM signal after transmission of 600-km SSMF fiber and 400-ps differential-group-delay. The performance of 110-Gb/s CO-OFDM signal is characterized by measuring the individual sub-band at 3.33 Gb/s.

OCIS codes: (060.2360) Fiber optics links and subsystems, (060.1660) Coherent communications

1. Introduction

Optical OFDM has recently been demonstrated beyond 100-Gb/s via offline signal processing [1]-[5]. For practical applications, real-time implementation of optical OFDM reception is imperative. There have been recently reports on optical OFDM transmitter [6, 7], receiver [8, 9], and transceiver [10]. With the limit of state-of-art silicon technology at 40 GS/s [11], it is difficult to improve data rate by increasing the sampling rate of off-shelf analogy-to-digital convertors (ADCs). Multi-band OFDM has been proposed to alleviate bandwidth constraint of ADC and it has been shown that a part of the OFDM spectrum can be carved out and detected at a fraction of the overall data rate [1-2, 9]. A multi-band 54-Gb/s real-time CO-OFDM reception has been demonstrated [9]. However all the real-time coherent optical OFDM (CO-OFDM) experiments [8, 9] have not included either chromatic dispersion or polarization-mode dispersion (PMD) effects. In this paper, we show a demonstration of field-programmable gate array (FPGA) based multi-band real-time CO-OFDM receiver at a data rate of 110-Gb/s by characterising the performance of its individual sub-band at 3.33-Gb/s. The multi-band CO-OFDM signal is successfully received and recovered after 600-km recirculation loop transmission and 400-ps differential-group-delay (DGD). To the best of our knowledge, this is the record real-time data rate for coherent OFDM reception with some realistic transmission distance and PMD effects.

2. Experimental Setup

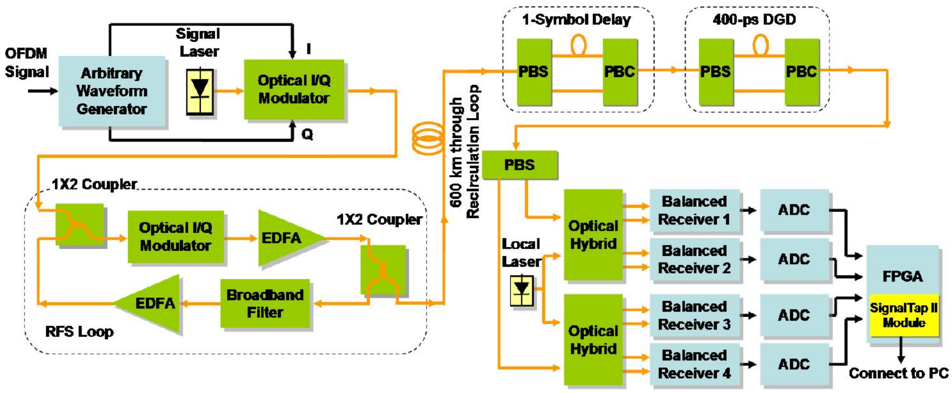

Fig. 1: Experiment setup for real-time CO-MIMO-OFDM reception with 600-km transmission and 400-ps DGD.

Fig. 1 shows the experimental configuration of multi-tone generation and real-time CO-OFDM reception. The transmitted data stream consisting of pseudo-random bit sequences (PRBS) of length 2^{15}-1 is first mapped onto three OFDM sub-bands with 4-QAM modulation. The 3 OFDM sub-bands were generated by an arbitrary waveform generator (AWG) at 6-GS/s. Each sub-band contains 46 subcarriers of 4-QAM modulation and 18 unfilled subcarriers. Two gap-bands with 21 unfilled subcarriers each are placed at two ends of the central sub-band, two gap-bands with 11 unfilled subcarriers are at left end of the left sub-band and right end of right sub-band, which allows them to be eventually distributed when patched with other tones. The 3 sub-bands together with 64 unfilled subcarriers are converted to the time domain via inverse Fourier transform (IFFT) with size of 256. 1/8 of cyclic-prefix ratio is used, resulting in an OFDM symbol size of 288. The total number of OFDM symbols in each frame is 504, with the first and third ones acting as timing and frequency offset estimation sequence and the second and fourth ones left blank. In the next 32 training symbols odd ones are normally modulated with transmitted data while even ones are unfilled to form a pattern of alternative polarization launch after polarization multiplexing. The two sub-bands around the central one are pre-equalized to compensate the frequency roll-off of AWG as shown in Fig. 2. The base-band RF signal is then directly up converted to optical domain through an optical I/Q modulator. At the output of modulator the optical signal is fed into a recirculating frequency shifter (RFS) to generate 11 uncorrelated sub-bands OFDM signal (see Fig. 2). The RFS is consisted of a closed fiber loop, an I/Q modulator, and optical amplifiers to compensate the frequency conversion loss. The I/Q modulator is driven with two equal but 90 degree phase shifted 6 GHz RF tones through I and Q ports, to induce a frequency shifting to the input optical signal [12]. The recirculating loop enables replicating multiple copies by one step per circulation if the initial optical OFDM signal is supplied. The signal is fed into a polarization splitter, delayed by one OFDM symbol and recombined to emulate two independent transmitters onto two polarizations. The polarization multiplexed CO-OFDM signal is then coupled into a recirculation loop comprising 100-km standard single mode fiber (SSMF) and a two-stage EDFA to compensate the loss. The CO-OFDM signal is coupled out from the loop after 6 circulations and fed into a PMD emulator imposing 400-ps DGD onto the signal. The optical spectrum of CO-OFDM signal after RFS and polarization multiplexing is depicted in Fig. 3.

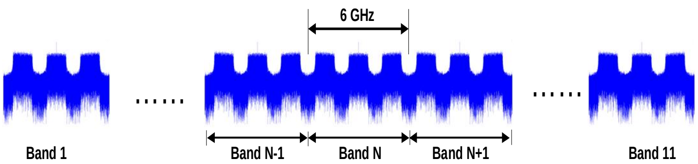

Fig. 2: Conceptual diagram of the 11-band CO-OFDM signal.

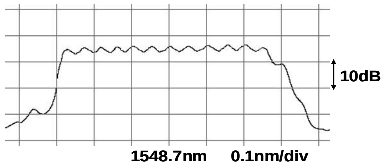

Fig. 3: Optical spectrum of 110-Gb/s CO-OFDM signal at back-to-back transmission.

At the receiver side, direct optical-to-RF down-conversion is employed. The principle of signal processing procedures is the same as [8]. Only one sub-band is detected at a time and others are filtered out by two 575-MHz anti-alias LPFs before ADCs. The detected RF signals are then sampled with four high speed ADCs at 1.5-GS/s with 7-bit resolution. The signal is transmitted via LVDS interface onto FPGA through 1:2 multiplexed outputs, which lowers the rate down to 750-MS/s. The multiple inputs are received and de-multiplexed into 4 channels at 375-MS/s in the FPGA for further processing. After all the OFDM signal processing, the recovered data are compared with transmitted ones in FPGA and the errors are counted. This error count, together with transmitted OFDM symbol numbers, is sampled by SignalTap II debugging module and transported via JTAG cable to PC for BER collection.

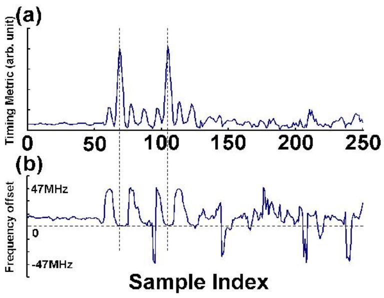

Fig. 4: (a) Timing metric for one polarization CO-MIMO-OFDM signal; (b) Frequency offset estimate for the CO-MIMO-OFDM signal.

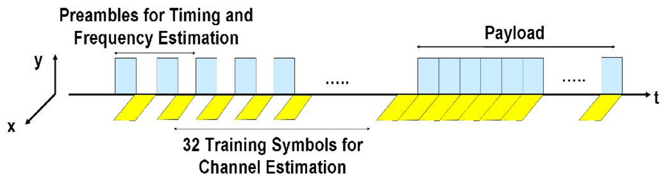

Fig. 5: The time-domain representation of the dual-polarization OFDM block including training symbols for timing and frequency synchronization, channel estimation, and payload. 'x' and 'y' represent two polarization components.

3. Signal Processing Algorithms

The CO-MIMO-OFDM receiver architecture is divided into nine stages: (1) timing synchronization, (2) frequency synchronization, (3) CP removal to recover OFDM block, (4) FFT to recover the frequency-domain symbols, (5) phase estimation for training symbols, (6) channel estimation, (7) Jones Matrix inversion to recover two polarization signals, (8) phase estimation for payload symbols, (9) symbol decision, error accumulation and BER computation. Some stages of signal processing are discussed in detailed below:

(i) Timing synchronization. In this stage, the OFDM symbol is properly delineated to avoid inter-symbol interference. We use a time-domain preamble [13] that is partitioned into four segments. To improve the accuracy of frequency offset estimation two training symbols are used for timing and frequency estimation. The timing metric of real-time data is shown in Fig. 4(a).

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(ii) Frequency synchronization. Frequency offset between signal laser and local laser must be estimated and compensated before further processing. Fig. 4(b) demonstrates the estimated frequency offset from two training sequences. According to the scheme in [13], the calculated values at timing estimate points are estimated frequency offsets. Average of two frequency offset estimations is used for frequency offset compensation to improve accuracy.

(iii) Channel estimation. The channel matrix $\boldsymbol{H}$ is estimated by sending 32 OFDM symbols using alternative polarization launch [8-9]. They are generated by filling the odd symbols with normal transmitted data, while leaving the even symbols blank. After the polarization multiplexing, the training symbols form a pattern of alternative polarization launch for two consecutive OFDM symbols as depicted in Figure 5. The four elements of channel matrix $\boldsymbol{H}$ is computed as follows: the two elements of the first and second column of $\boldsymbol{H}$ can be estimated using odd and even number of the pilot symbols, respectively [6].

4. Measurement and Discussion

Fig. 6 shows the BER performance of 110-Gb/s 4-QAM CO-OFDM signal at back-to-back transmission with and without 400-ps DGD. The polarization in the system is left free-running and no manual polarization control is used during the time of the measurement. The inset shows a typical constellation diagram for the detected CO-OFDM signal. Each point in this figure is obtained by averaging over 30 OFDM transmission blocks. The combined laser linewidth is about 100-kHz. A BER of 10^{-3} can be observed at an OSNR of 22 dB (ASE noise bandwidth of 0.1 nm) for 4-QAM. It is noted that the difference of BER performance for two polarization signals at the same OSNR is less than 0.5 dB and OSNR penalty for 400-ps DGD is smaller than 1 dB at the BER of 10^{-3}. We also measure the performance after 600-km recirculation loop transmission. The launch power is about -10 dBm. Fig. 7 shows the BER performance for the 11 tones at the reach of 600 km with and without 400-ps DGD, and it can be seen that all the tones can achieve a BER better than 2×10^{-3}, the FEC threshold with 7 % overhead. It is noted that there is no observable penalty for 400-ps DGD. The BER performance for this real-time 110-Gb/s CO-MIMO-OFDM transmission is limited by two factors: (i) the noise accumulation for the edge bands that have gone through most of the frequency shifting, and (ii) the large phase drift due to long OFDM symbol length by using relatively low sampling rate of 1.5-GS/s, which can be avoided by using ADCs with higher sampling rate. Nevertheless, our demonstration has achieved the real-time characterization of CO-OFDM signal after 600-km transmission and relatively large DGD.

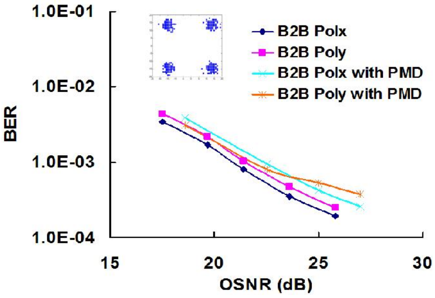

Fig. 6: BER performance for CO-OFDM signals at back-to-back transmission with and without 400 ps PMD.

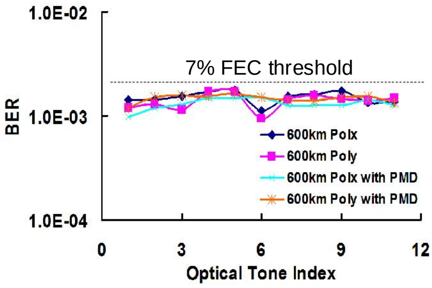

Fig. 7: BER performance for individual OFDM tones after 600-km transmission.

5. Conclusion

We have demonstrated 110-Gb/s real-time CO-OFDM reception after 600-km transmission and 400-ps DGD based on FPGA. The BER performance of each tone is better than 7% FEC threshold of 2×10^{-3}. The OFDM signal is generated with a recirculating frequency shifter producing 11 tones each comprised of 3 sub-bands.

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