Experimental Demonstration of 28 Gbaud QPSK and 16-QAM Zero-Guard-Interval CO-OFDM Transmissions

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Abstract *28 Gbaud QPSK and 16-QAM zero-guard-interval (ZGI) CO-OFDM transmission with only 1.34% overhead for OFDM processing is reported. The high tolerance of ZGI CO-OFDM to residual inter-symbol interference and imperfect frame synchronization is also demonstrated.*

Introduction

High spectral efficiency modulation formats have been actively investigated in order to satisfy the ever-increasing demand for channel capacity in optical communications[1]. Coherent optical (CO) orthogonal frequency-division multiplexing (OFDM) is an attractive format because of its compact spectrum. However, in conventional CO-OFDM systems the spectral efficiency benefit is limited due to the large overhead such as the long cyclic prefix (CP) required to accommodate accumulated chromatic dispersion (CD)[2]. Reduced-guard-interval (RGI) CO-OFDM compensates CD using an overlapped frequency domain equalizer (OFDE) before OFDM demodulation and therefore significantly reduces the required CP length[3]. High spectral efficient transmission has been demonstrated using RGI CO-OFDM[3,4]. Nevertheless, the CP is still required to avoid residual inter-symbol interference (ISI) such as polarization mode dispersion (PMD). This introduces a non-negligible overhead especially for short symbol durations.

In this paper, we report experimental zero-guard-interval (ZGI) CO-OFDM transmission using the equalization scheme proposed in our previous work[5], which completely removes CP from data symbols. 28 Gbaud QPSK transmission over 5120 km of standard single mode fiber (SSMF) with 7% forward error correction (FEC) overhead and 28 Gbaud 16-QAM transmission over 1280 km of SSMF with 20% FEC overhead using erbium-doped fiber amplifier (EDFA) only amplification is demonstrated. The total OFDM processing overhead for both cases is only 1.34%. To the best of our knowledge, this is the highest baud rate with the lowest OFDM processing overhead for electrically generated single band CO-OFDM systems reported. Moreover, we show that ZGI CO-OFDM with no CP can achieve much higher tolerance to residual ISI than RGI CO-OFDM with 4 samples CP.

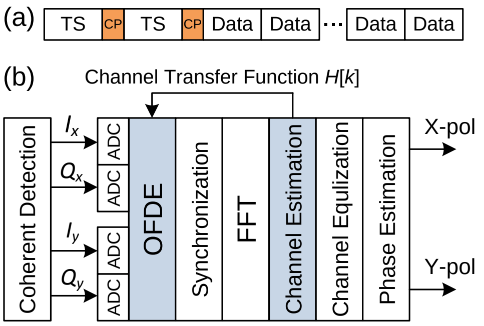

Fig. 1: (a) Transmitted ZGI CO-OFDM frame. (b) Block diagram of ZGI CO-OFDM receiver.

Principle of ZGI CO-OFDM

Fig. 1(a) shows the transmitted frame for ZGI CO-OFDM systems. The CP is only inserted after each training symbol (TS) and no CP is added to data symbols[5]. The receiver diagram is depicted in Fig. 1(b). For each OFDM frame, the TS's are first passed through an OFDE for CD compensation. The inserted CP is used to prevent the residual ISI from affecting the following channel estimation using the TS's. The intra-symbol frequency averaging (ISFA) can be used to remove the noise interference in channel estimation[6]. Then frequency domain interpolation (FDI) is applied to map and expand the estimated channel transfer function $H[k]$ (with typically a small size) to H_{FDI} which has the same size as the FFT/IFFT in the OFDE. Afterwards, H_{FDI} is applied to update the coefficients of the OFDE as follows[5]:

$$H_{new}^{-1} = H_{old}^{-1} \cdot H_{FDI}^{-1} \qquad (1)$$

where H_{old}^{-1} contains the old coefficients, which are initially used for CD compensation only. With the updated coefficient matrix H_{new}^{-1}, the OFDE is now capable of compensating for all the ISI and no CP is required for the following data symbols. After that, the TS's need to be passed through the OFDE and to be used for channel estimation again in order to compensate for the imperfection of H_{FDI} caused by the FDI.

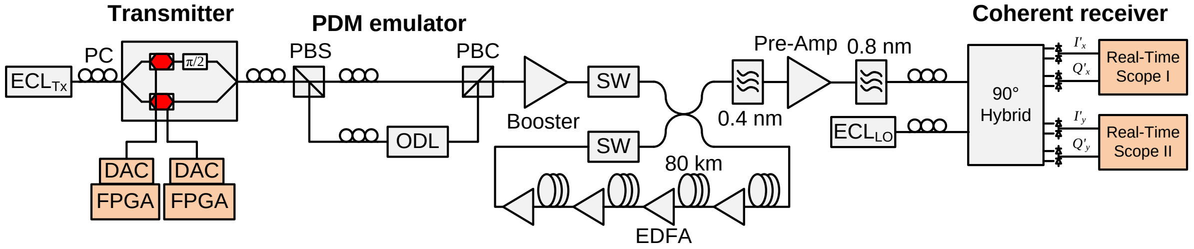

Fig. 2: Experimental setup. ECL: external cavity laser. PC: polarization controller. FPGA: field-programmable gate array. PBS/PBC: polarization beam splitter/combiner. ODL: optical delay line. SW: switch.

Experimental Setup

Fig. 2 shows the experimental setup. At the transmitter, the OFDM waveform was generated by offline digital signal processing (DSP) in Matlab. The pseudo random binary sequence (PRBS) was modulated by either QPSK or 16-QAM format onto 111 subcarriers. 1 pre-emphasized pilot subcarrier[7] was inserted for phase estimation. The DC subcarrier was unfilled. Via an IFFT with a size of 128, the time domain waveform was created with an oversampling ratio of 1.13. For RGI CO-OFDM, 4 samples CP were inserted into all symbols, while for ZGI CO-OFDM 12 samples CP (chosen to align the TS's without modifying the dual-polarization delay) were inserted into only TS's. In both systems, one pair of correlated dual-polarization (CDP) TS's[8] were sent for the purpose of channel estimation and equalization for 500 data symbols, which were used for the final BER calculation. Therefore, the total OFDM overhead was 4.43% (=1/111+2/500+4/128) and 1.34% (=1/111+2.19/500) for RGI and ZGI CO-OFDM, respectively.

After pre-emphasis to compensate for the transmitter roll-off, the real and imaginary parts of the waveform were stored in the memory of two FPGA boards driving two 32 Gs/s digital-to-analog converters (DACs) with 6 bit resolution for the generation of the 28 Gbaud electrical OFDM signals. Optical IQ modulation was employed for electrical-to-optical conversion. Polarization-division-multiplexed (PDM) signal was formed using the PDM emulator with a delay of 6 RGI CO-OFDM symbols (24.8 ns) in order to fully de-correlate the signal of the two polarizations. The signal amplified by a booster was then launched into a re-circulating loop, which consists of 4 spans each having 80 km SSMF and an EDFA with 5 dB noise figure. The launch power was -2 dBm, which was optimized for the transmissions. At the receiver, the signal out of the loop was filtered, amplified and filtered again before being coherently detected. Two real-time scopes operating at 80 Gs/s with a 33 GHz analog bandwidth were used to digitize the signal. The main procedures of the offline processing have been introduced in the previous section. For the OFDE, the FFT/IFFT size was 4096 with 850 overlapped samples. ISFA was applied in channel estimation for all systems.

Experimental Results

Fig. 3 and Fig. 4 show the measured BER as a function of transmission distance for QPSK and 16-QAM, respectively. We can see that ZGI CO-OFDM performs as well as the RGI CO-OFDM. In particular, with QPSK modulation they can achieve a transmission distance up to 5120 km with a BER below 3.8×10^{-3}, which corresponds to the BER threshold of a 7% overhead FEC. For 16-QAM, due to the low effective number of bits (ENOB) at high frequencies of our DACs, the transmission distance considering 7% FEC overhead is limited to only 320 km. However, the reach of both RGI and ZGI systems is increased to 1280 km when a 20% overhead FEC (2×10^{-2} BER threshold) is employed.

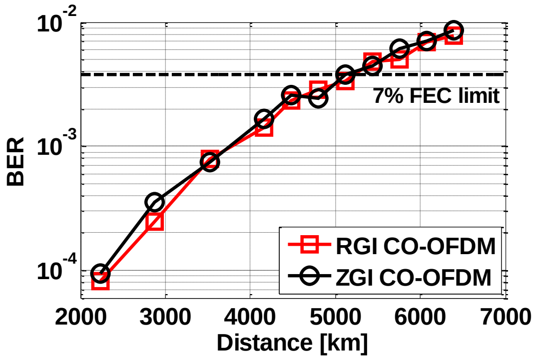

Fig. 3: Measured BER vs. transmission distance for 28Gbaud QPSK signal.

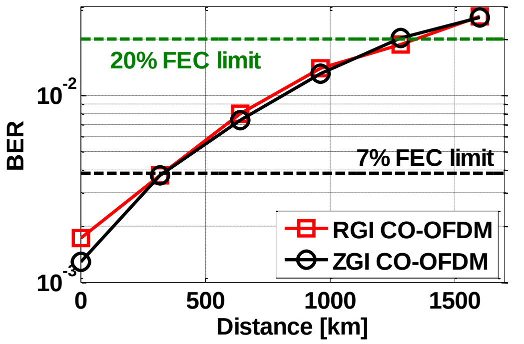

Fig. 4: Measured BER vs. transmission distance for 28Gbaud 16-QAM signal.

Next, we show that ZGI CO-OFDM not only reduces the CP overhead to zero but also significantly improves the system tolerance to residual ISI. Fig. 5 shows the measured Q-factor (derived from BER) penalty versus residual CD for the two systems. The Q-factor with no residual CD is used as the reference. For RGI CO-OFDM, there is no penalty with a residual CD below 550 ps/nm, in which case the memory length is less than the CP length, i.e. 4 samples. However, beyond 550 ps/nm the penalty increases as the residual CD gets larger, and it reaches 2.2 dB and 3.4 dB with 2800 ps/nm residual CD for QPSK and 16-QAM, respectively. For ZGI CO-OFDM, we observe a higher tolerance to residual CD. Particularly, with the residual CD up to 2800 ps/nm the Q-factor penalty of ZGI CO-OFDM stays below 0.7 dB for both QPSK and 16-QAM. The tolerance can be even further improved by increasing the CP length of TS's at the expense of a negligible additional overhead.

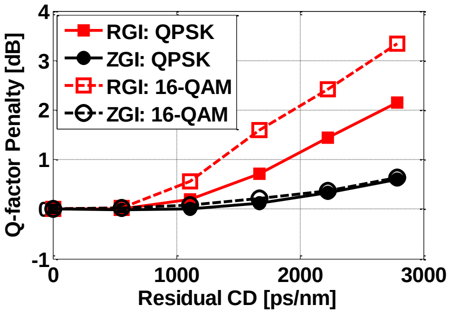

Fig. 5: Measured Q-factor penalty vs. residual CD. QPSK: 5120 km. 16-QAM: 1280 km.

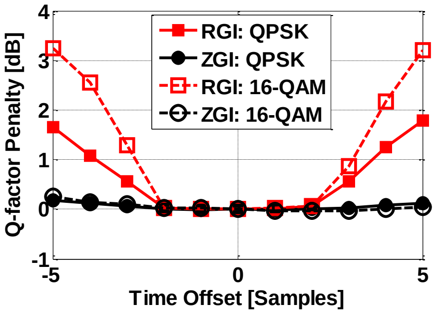

Fig. 6: Measured Q-factor penalty vs. time offset. QPSK: 5120 km. 16-QAM: 1280 km.

The conventional autocorrelation based frame synchronization using two identical symbols (or sequences) might introduce a time offset in finding the beginning of the OFDM symbol[9]. This time offset can be tolerated by increasing the CP length. Fig. 6 shows the Q-factor penalty as a function of time offset (in samples at 32 Gs/s) for RGI and ZGI CO-OFDM systems. The Q-factor with no time offset is used as the reference. The negligible penalty for RGI with time offset from -2 to 2 samples is expected since it has 4 samples CP, which avoids ISI. However, for time offset larger than 2 samples, the penalty increases significantly. It goes up to 1.8 and 3.2 dB with 5 samples offset for QPSK and 16-QAM, respectively. By comparison, the penalty of ZGI CO-OFDM stays below 0.3 dB with time offset from -5 to 5 samples for both QPSK and 16-QAM, demonstrating its high tolerance to imperfect frame synchronization.

Tab. 1: Comparison of CP overhead.

	QPSK (5120 km) ($=N_{CP}/N_{IFFT}$)	16-QAM (1280 km) ($=N_{CP}/N_{IFFT}$)
Conv	15.9% (=650/4096) 31.7% (=650/2048)	7.8% (=160/2048) 15.6% (=160/1024)
RGI	3.13% (=4/128) 6.25% (=4/64)	3.13% (=4/128) 6.25% (=4/64)
ZGI	0%	0%

Tab. 1 shows the required CP overhead (for data symbols) comparison for conventional (Conv), RGI and ZGI CO-OFDM systems calculated with the parameters in our experimental setup. The CP length N_{CP} just covers the CD-induced channel memory length for conventional OFDM. $N_{CP} = 4$ is assumed for RGI CO-OFDM to avoid residual ISI. As a conclusion, ZGI CO-OFDM saves CP overhead by 3.13% to 6.25% and 15.6% to 31.7% compared to RGI and conventional CO-OFDM, respectively, depending on the IFFT size N_{IFFT}. Moreover, it has been shown that using a smaller N_{IFFT} to generate the OFDM signal, in which case the advantage of ZGI CO-OFDM is larger, improves the system tolerance to fiber nonlinearities[10], laser phase noise[11] and frequency offset[3].

Conclusions

In this paper, we experimentally demonstrated 28 Gbaud QPSK and 16-QAM zero-guard-interval (ZGI) CO-OFDM transmissions with only 1.34% OFDM processing overhead. Moreover, we showed that ZGI CO-OFDM achieves higher tolerance to residual inter-symbol interference and imperfect frame synchronization compared to reduced-guard-interval (RGI) CO-OFDM with 4 samples cyclic prefix.

References

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