Single channel and WDM transmission of 28 Gbaud zero-guard-interval CO-OFDM

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Abstract: We report on the experimental demonstration of single channel 28 Gbaud QPSK and 16-QAM zero-guard-interval (ZGI) CO-OFDM transmission with only 1.34% overhead for OFDM processing. The achieved transmission distance is 5120 km for QPSK assuming a 7% forward error correction (FEC) overhead, and 1280 km for 16-QAM assuming a 20% FEC overhead. We also demonstrate the improved tolerance of ZGI CO-OFDM to residual inter-symbol interference compared to reduced-guard-interval (RGI) CO-OFDM. In addition, we report an 8-channel wavelength-division multiplexing (WDM) transmission of 28 Gbaud QPSK ZGI CO-OFDM signals over 4160 km.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications.

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1. Introduction

The ever-increasing demand for channel capacity of optical transport systems has led to an active investigation into highly spectrally efficient modulation formats [1]. Attributed to the inherent compact spectrum, coherent optical (CO) orthogonal frequency-division multiplexing (OFDM) is regarded as a potential candidate for spectrally efficient transmission systems. Conventional CO-OFDM systems are resilient to linear effects such as chromatic dispersion (CD) by inserting a very long cyclic prefix (CP) to prevent inter-symbol interference (ISI) [2, 3]. However, the large CP overhead compromises the spectral efficiency benefit. Reduced-guard-interval (RGI) CO-OFDM was later proposed to significantly reduce the CP overhead by compensating CD using an overlapped frequency domain equalizer (OFDE) before the OFDM demodulation at the expense of additional complexity for equalization [4]. Along with high order QAM, many high spectrally efficient RGI CO-OFDM transmissions have been demonstrated [4, 5]. Nevertheless, a short CP, which introduces a non-negligible overhead especially for short symbol durations, is still needed to accommodate the residual inter-symbol interference (ISI) such as residual CD, polarization mode dispersion (PMD) and narrowing filtering effect.

We have previously proposed a zero-guard-interval (ZGI) CO-OFDM system which doesn't require any CP inserted in-between data symbols [6]. In this paper, we describe in more detail the first experimental demonstration of ZGI CO-OFDM transmission reported at the 2012 European Conference on Optical Communication (ECOC) [7]. Through the link with standard single mode fiber (SSMF) and erbium-doped fiber amplifiers (EDFA), we demonstrate a single channel 28 Gbaud QPSK transmission over 5120 km of fiber with 7% forward error correction (FEC) overhead and a 28 Gbaud 16-QAM transmission over 1280 km of SSMF with 20% FEC overhead. The total overhead for OFDM processing is only 1.34%. Moreover, the higher tolerance to residual ISI of ZGI CO-OFDM with no CP with respect to RGI CO-OFDM with 4 samples CP is shown. This is also the first experimental demonstration of an electrically-generated single-band OFDM system with a baud rate up to 28 Gbaud. In this work, we additionally report a wavelength-division multiplexing (WDM) transmission of 8 × 112 Gb/s ZGI CO-OFDM over 4160 km distance.

2. Principle of ZGI CO-OFDM

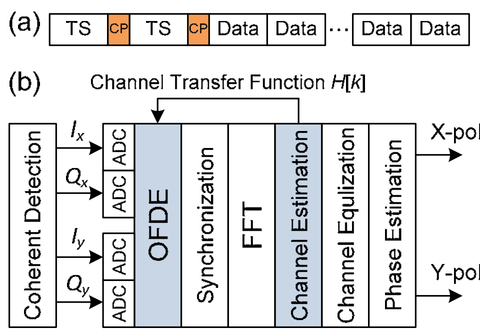

Fig. 1. (a) Transmitted ZGI CO-OFDM frame. (b) Block diagram of ZGI CO-OFDM receiver.

As plotted in Fig. 1(a), the CP is only inserted after each training symbol (TS) in the transmitted ZGI CO-OFDM frame, and no CP is added in-between data symbols. In the signal processing at the receiver, of which the block diagram is depicted in Fig. 1(b), the TS's are first passed through an OFDE for CD compensation. The inserted CP after each TS prevents the residual ISI from affecting the following channel estimation. The estimated channel transfer function $H[k]$ can be refined using the intra-symbol frequency averaging (ISFA), which removes the noise interference [8]. The basic idea of ZGI CO-OFDM is to use the OFDE to compensate all linear effects, which is realized by updating the coefficients of the OFDE based on the OFDM channel estimation as illustrated in Fig. 1(b). In addition, the frequency domain interpolation (FDI) is required to expand H[k], which normally has a small size, to H_{FDI} with the same size as the fast Fourier transform (FFT) in the OFDE. After that, the new OFDE coefficients can be obtained as follows

$$H_{new}^{-1} = H_{old}^{-1} \cdot H_{FDI}^{-1} \tag{1}$$

where H_{old}^{-1} contains the old coefficients, which are initially set to compensate for CD only. With the updated coefficient matrix H_{new}^{-1}, almost all the ISI can be compensated at the OFDE, and thus CP is not required for the following data symbols. However, in order to compensate for the imperfection of H_{FDI} caused by the FDI, the TS's need to be passed through the OFDE and to be used for channel estimation again. The estimated channel matrix

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is now used for the OFDM channel equalization. More details of the ZGI CO-OFDM scheme can be found in [6]. Moreover, it is shown in [6] that compared to RGI CO-OFDM the additional computation complexity of ZGI CO-OFDM is reasonably small (normally < 15%).

3. Experimental setup and results

3.1 Single channel transmission

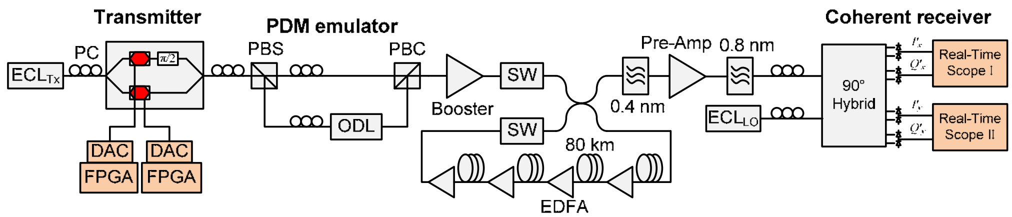

Fig. 2. Experimental setup. ECL: external cavity laser. PC: polarization controller. PBS/PBC: polarization beam splitter/combiner. ODL: optical delay line. SW: switch.

Figure 2 shows the experimental setup. In the offline digital signal processing (DSP) at the transmitter, the pseudo random binary sequence (PRBS) was mapped to either QPSK or 16-QAM symbols on 111 subcarriers. In addition, one pre-emphasized pilot subcarrier was inserted for phase estimation, and the DC subcarrier was unfilled. Then via an inverse fast Fourier transform (IFFT) with a size of 128 and the pre-emphasis to compensate for the transmitter roll-off, the time domain waveform was generated with an oversampling ratio of 1.13. For ZGI CO-OFDM, a 12-sample CP (chosen to align the TS's without modifying the dual-polarization delay) was inserted after each TS, while no CP was added to the data symbols. For comparison, we also conducted the RGI CO-OFDM transmissions, for which a 4-sample CP was added after both the TS's and data symbols. In both systems, one pair of TS's for channel estimation was inserted at the beginning of each OFDM frame which contained 500 data symbols. Therefore, the overall overhead including pilot subcarrier, training symbol and CP was 1.34% (= 1/111 + 2.19/500) and 4.43% (= 1/111 + 2/500 + 4/128) for ZGI and RGI CO-OFDM systems, respectively.

The OFDM samples were stored in the memory of two field-programmable gate array (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 consisted 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 the channel estimation for all systems.

The back-to-back performance of QPSK and 16-QAM is shown in Fig. 3(a) and 3(b), respectively. First, ZGI CO-OFDM achieves a similar performance as RGI CO-OFDM for both modulation formats. Due to the low effective number of bits (ENOB) of our DACs at high frequencies, a >7.5 dB optical signal-to-noise ratio (OSNR) penalty is observed for 16-QAM at a bit error rate (BER) around 3.8×10^{-3}. However, for QPSK the OSNR penalty is only 2 dB, because for the same BER the loaded amplified spontaneous emission (ASE) noise is dominant rather than the impairment from the transmitter.

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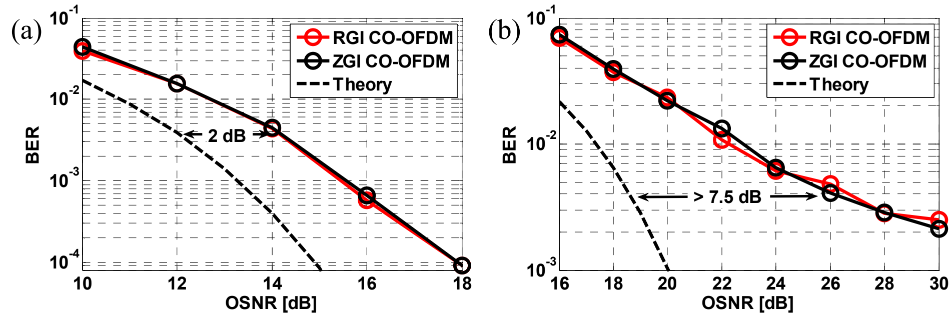

Fig. 3. Measured BER vs. OSNR (0.1nm) for (a) QPSK and (b) 16-QAM signals.

Figure 4(a) and 4(b) show the transmission performance for QPSK and 16-QAM, respectively. Again, ZGI CO-OFDM without CP performs as well as RGI CO-OFDM with 4 samples CP. In particular, for QPSK they both achieve a transmission distance of 5120 km with a 7% FEC overhead (BER = 3.8×10^{-3}). For 16-QAM, we can see that the BER is already larger than 1×10^{-3} at back-to-back due to the low ENOB at high frequencies as mentioned earlier. Therefore, the transmission distance considering 7% FEC overhead is limited to only 320 km. However, with a 20% overhead FEC (2×10^{-2} BER threshold) employed the distance can be increased to 1280 km.

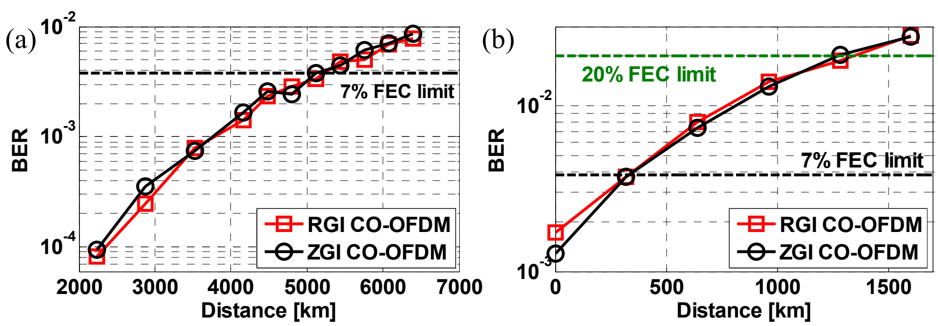

Fig. 4. Measured BER vs. transmission distance for (a) 28 Gbaud QPSK and (b) 16-QAM signals.

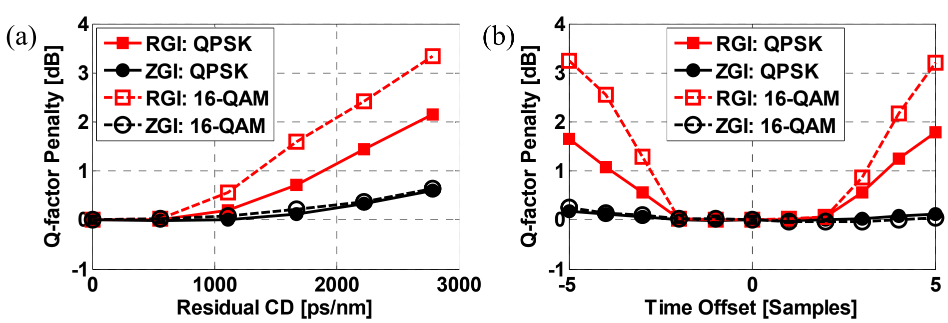

Fig. 5. Measured Q-factor penalty vs. (a) residual CD and (b) time offset. QPSK: 5120 km. 16-QAM: 1280 km.

Next, we show that ZGI CO-OFDM not only removes the CP from data symbols but also enhances the system resilience to residual ISI including residual CD and time offset. First, the measured Q-factor (derived from BER) penalty versus residual CD for the ZGI and RGI system is shown in Fig. 5(a). For the RGI system, the penalty is negligible when the residual

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CD is below 550 ps/nm, since the 4-sample CP is longer than the corresponding memory length. However, with the residual CD larger than 550 ps/nm, where the 4-sample CP is not enough, the penalty increases as the residual CD gets larger, and it reaches 2.2 dB and 3.4 dB with a 2800 ps/nm residual CD for QPSK and 16-QAM, respectively. By comparison, ZGI CO-OFDM manifests a much higher tolerance to residual CD. In particular, the Q-factor penalty of the ZGI system stays below 0.7 dB for both QPSK and 16-QAM even with a residual CD up to 2800 ps/nm.

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]. Such a time offset to also a linear effect. Figure 5(b) shows the Q-factor penalty versus time offset (in samples at 32 Gs/s). The Q-factor with no time offset is used as the reference. For the RGI system the penalty is negligible with the time offset from −2 to 2 samples since it contains 4 samples CP. However, with the time offset beyond this range the penalty is significantly increased, which goes up to 1.8 and 3.2 dB with 5 samples offset for QPSK and 16-QAM, respectively. On the other hand, the penalty of the ZGI system is less than 0.3 dB with a time offset from −5 to 5 samples for both QPSK and 16-QAM, showing its improved resilience to imperfect frame synchronization. It should be noted that the tolerance of ZGI CO-OFDM to residual ISI is determined by the CP length in the TS's, and it can be further improved by increasing the CP length, which only induces a very small overhead.

Table 1. Comparison of the 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%

Table 1 shows the comparison of the CP overhead (for data symbols) for conventional (Conv), RGI and ZGI CO-OFDM systems based on the parameters of our experimental setup. The CP length N_{CP} is slightly longer than the CD-induced channel memory length for conventional OFDM. We assume N_{CP} = 4 for RGI CO-OFDM to avoid residual ISI. In conclusion, the ZGI system can save the CP overhead by 3.13% to 6.25% and 7.8% to 31.7% with respect to RGI and conventional CO-OFDM, respectively, depending on the IFFT size N_{IFFT}. Moreover, it has been shown that generating the OFDM signal with a smaller N_{IFFT}, in which case the advantage of ZGI CO-OFDM is more significant, enhances the system tolerance to fiber nonlinearities, laser phase noise [10] and frequency offset [4].

3.2 WDM transmission

In this section, we demonstrate a WDM transmission of 8 × 112 Gb/s ZGI CO-OFDM signals with 28 Gbaud QPSK format. Figure 6(a) depicts the block diagram of the transmitter configuration. 8 distributed feedback (DFB) laser sources spaced by 50 GHz were combined using an arrayed waveguide grating (AWG), before being bulky modulated with ZGI CO-OFDM signals. The PDM signal was then interleaved into odd and even channels. The lengths of the two paths were different, leading to a de-correlation of adjacent channels. The channels were then combined and transmitted. The spectrum of the generated WDM signal is plotted in Fig. 6(b). In the re-circulating loop, a waveshaper was employed after the second EDFA as a gain flattening filter. At the receiver, the ECL was tuned to pick the desired channel for BER measurement. Two normal pilot subcarriers were employed for phase estimation, leading to an overall overhead of 2.24%. Figure 6(c) presents the BER for all channels after 3200 km and 4160 km transmissions. It can be seen that the BERs are all below 3.8×10^{-3} after 4160 km transmissions. In addition to the low overhead and long reach of the ZGI system, this transmission also demonstrates its high tolerance to the laser phase noise as the DFB lasers were employed at the transmitter. This is attributed to the short symbol duration (N_{IFFT} = 112), which significantly reduces the phase noise induced inter-carrier interference [10].

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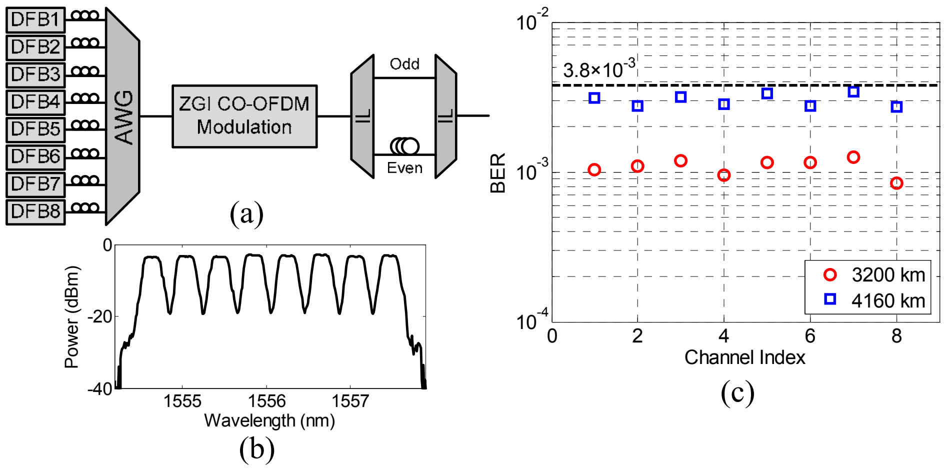

Fig. 6. (a) The transmitter for the WDM transmission. IL: interleaver. (b) The spectrum of the generated 8-channel WDM signal. (c) The BER performance of all channels.

4. Conclusions

In this paper, we experimentally demonstrate single channel 28 Gbaud zero-guard-interval (ZGI) CO-OFDM transmissions over 5120 km of fiber for QPSK (7% FEC) and 1280 km of fiber for 16-QAM (20% FEC). The OFDM processing overhead is only 1.34%. Moreover, we show that ZGI CO-OFDM without cyclic prefix (CP) for data symbols achieves higher tolerance to residual inter-symbol interference and imperfect frame synchronization compared to reduced-guard-interval (RGI) CO-OFDM with 4 samples CP. In addition, we report the 8-channel WDM transmission of 28 Gbaud QPSK (112 Gb/s) ZGI CO-OFDM over 4160 km distance with all DFB lasers employed at the transmitter.

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