Low overhead and nonlinear-tolerant adaptive zero-guard-interval CO-OFDM

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Abstract: We propose an adaptive channel estimation (CE) method for zero-guard-interval (ZGI) coherent optical (CO)-OFDM systems, and demonstrate its performance in a single channel 28 Gbaud polarization-division multiplexed ZGI CO-OFDM experiment with only 1% OFDM processing overhead. We systematically investigate its robustness against various transmission impairments including residual chromatic dispersion, polarization-mode dispersion, state of polarization rotation, sampling frequency offset and fiber nonlinearity. Both experimental and numerical results show that the adaptive CE-aided ZGI CO-OFDM is highly robust against these transmission impairments in fiber optical transmission systems.

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References and links
1. Introduction

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) is regarded as a potential candidate for spectrally efficient and high capacity transmission systems attributed to its inherent compact spectrum [1,2]. In CO-OFDM, cyclic prefix (CP) is used to eliminate virtually all inter-symbol interferences (ISI) induced by, for example, chromatic dispersion (CD), polarization mode dispersion (PMD) and narrow filtering effects. Besides, training symbols (TS) and pilot subcarriers (PS) are needed to perform the channel estimation (CE) and laser phase noise compensation (LPNC) in order to successfully receive OFDM symbols [1–3]. Large overhead required by CP, CE and LPNC scarifies the spectral efficiency (SE) benefit of CO-OFDM, making it less attractive compared to single carrier transmission systems.

Reduced-guard-interval (RGI) CO-OFDM was proposed to compensate for CD using an overlapped frequency domain equalizer (OFDE) and significantly reduce the CP overhead [4]. Zero-guard-interval (ZGI) CO-OFDM was later introduced to completely remove CP by first estimating the channel state information (CSI) using training symbols, and then feedback the CSI to the OFDE and compensate all ISI within the OFDE stage [5,6]. The reduced CP overhead of ZGI CO-OFDM not only increases the SE, but also provides the flexibility to design an optimum OFDM symbol size and offers some additional benefits: (1) reduced computational efforts with a reduced OFDM symbol size, (2) improved laser phase noise tolerance, (3) improved sampling frequency offset (SFO) tolerance, and (4) potentially higher intra-channel fiber nonlinear tolerance compared with the Nyquist single carrier system [4–8]. Moreover, ZGI CO-OFDM enhances the system resilience to residual CD, PMD and timing synchronization offset compared with RGI CO-OFDM [5,6]. Therefore, ZGI CO-OFDM is a promising candidate among all of the CO-OFDM variations.

However, in ZGI CO-OFDM, a non-negligible overhead is still caused by training symbols (TS), which are transmitted periodically to probe the CSI and track channel temporal variations such as the state of polarization (SOP) rotation. In addition, a time domain moving averaging algorithm is usually applied to tens of repeated TS’s in order to reduce the impact of noise [3]. Therefore, the required TS overhead depends on both the rate of the time varying effects of the channel, which determines the required TS insertion frequency, and on the optical signal to noise ratio (OSNR), which is related to the required number of TSs to be averaged for each CE. This time averaging (TA) method achieves an accurate CE at the expense of a reduced SE. Intra-symbol frequency domain averaging (ISFA) method was proposed in [9] to reduce the number of TSs for each CE. However, the ISFA averaging length, or equivalently the accuracy of the CE, is limited by the frequency correlation between neighboring subcarriers [9].

Recently we proposed a decision feedback adaptive channel estimation method for ZGI CO-OFDM systems (denoted as Adaptive-ZGI), which achieves an accurate CE and improves the ability to track channel temporal variations without increasing the TS overhead [10]. The proposed method is essentially different than the blind estimation used in optically generated OFDM systems where each subcarrier is actually a single carrier system and hence can adopt the equalization techniques, such as constant modulus algorithm (CMA), from single carrier systems [11]. In this paper, we discuss the proposed method in more details and systematically study its robustness against various transmission impairments including residual CD, PMD, SFO, SOP and fiber nonlinearity. We experimentally demonstrate a single
channel 28-Gbaud (112 Gb/s) polarization-division multiplexing (PDM) QPSK Adaptive-ZGI CO-OFDM system with a total processing overhead of only 1.03%.

2. Principles of Adaptive-ZGI CO-OFDM

2.1 System design of Adaptive-ZGI

Figure 1(a) and 1(b) show the transmitted frame structures for the conventional ZGI (denoted as CON-ZGI) and Adaptive-ZGI, respectively. In CON-ZGI, correlated dual-polarization (CDP) TSs pairs are sent periodically at the beginning of each frame to capture the time varying effects [4]. In Adaptive-ZGI, only one pair of CDP TSs is inserted at the beginning of the data stream to initiate the CE procedure while the adaptive phase is fulfilled with a data aided decision feedback module. In both systems, CP (highlighted by red in Fig. 1(a) and (b)) is inserted only for TS.

The major receiver-side digital signal processing (DSP) diagram of the CON-ZGI and Adaptive-ZGI are depicted in Fig. 2. In both systems, TSs are first passed through an OFDE for CD compensation. The inserted CP for each TS prevents the residual ISI from affecting the following CE procedure.

An effective way to reduce the impact of noise in the CE procedure is to apply a moving average algorithm in either the time or the frequency domain, i.e., TA or ISFA methods. For TA method, the refined channel estimation is given by [3]

\[
\overline{H}(k) = \frac{1}{L} \sum_{n=1}^{L} H_n(k)
\]

where \(H_n(k)\) is the initial channel transfer function estimated with TSs for the \(k\)th subcarrier, \(n\) is the TS index, \(L\) is the averaging length (total number of TSs in this case), and \(\overline{H}(k)\) is the final estimation for the \(k\)th subcarrier. The TA method can achieve an accurate estimation as long as the channel transfer function does not change drastically during the training period, which is a reasonable assumption for a typical fiber transmission system. However, the
averaging length \( L \) for TA method requires tens of TSs to be transmitted for one CE process and hence seriously sacrifices the system SE. In addition, since the TS overhead depends both on the system OSNR and channel varying effects, there is a tradeoff between the accuracy of each CE and the channel temporal tracking speed at a fixed TS overhead.

The ISFA method, on the other hand, applies the moving average window in the frequency domain between neighboring subcarriers. And the ISFA process is denoted as [9]

\[
\begin{align*}
\overline{H}(k) &= \frac{1}{\min(k_{\text{max}}, k + m) - \max(k_{\text{min}}, k - m) + 1} \sum_{k' = k - m}^{k + m} H(k'), L = 2m + 1
\end{align*}
\]

where \( k_{\text{max}} \) and \( k_{\text{min}} \) are the maximum and minimum modulated subcarrier indexes, respectively. Typically, for the \( k \)th subcarrier, the averaging can be performed over subcarrier \( k \) and its \( m \) left neighbors and \( m \) right neighbors, or totally up to \( L = 2m + 1 \) adjacent subcarriers. But for edge subcarriers, the averaging is asymmetric due to the absence of either left or right subcarriers. The ISFA method achieves an accurate estimation with a reduced overhead only if all the subcarriers experience similar channel impairments. In the presence of ISI (caused by CD, PMD and etc.), however, the method suffers from an additional penalty due to the frequency de-correlation. And the penalty increases with the increase of the averaging length \( L \) [9]. However, despite of this drawback, the ISFA method is still popular when the system overhead becomes an important consideration and is thus used in the CON-ZGI system.

For the CON-ZGI, to partially mitigate the penalty caused by the imperfect averaging of ISFA, TS based CE with a small size ISFA aiming to remove noise interference is first performed to extract and feedback a coarse channel matrix \((H_{\text{coarse}})\) to the OFDE. The ISFA averaging length \( L_1 \) is limited by the amount of ISI. After the OFDE removes most of the ISI, a second time TS aided ISFA with a large averaging length \( L_2 \) enables an accurate CE \((H_{\text{fine}})\) and channel equalization [5]. Channel information is updated on a frame basis determined by the TS overhead.

For the Adaptive-ZGI, different DSP procedures are marked with the red lines in Fig. 2(b). The TS aided coarse CE is only used for initiating the feedback process. The following updating equalizers \( H_{\text{coarse}} \) could be designed with the decisions of the OFDM data symbols based on zero-forcing (ZF) algorithm or minimum mean square error criterion. Throughout the work we only consider the ZF-equalizer since the latter one requires the knowledge of noise spectral density which is usually unavailable to the receiver [12,13]. The ZF equalizer is given by [3,12]

\[
H_{\text{coarse}}(k) = R(k)S^+(k)
\]

where \( R(k) \) is the received signal on the \( k \)th subcarrier, \( S(k) \) denotes the transmitted TS at the initial training phase and the decisions of data symbols at the following adaptive phase, and the superscript + denotes the pseudo-inverse operation. Since data symbols do not count as overhead, an accurate \( H_{\text{fine}} \) can be obtained with TA method to remove noise in the CE process and be fed back to the OFDE (Fig. 2(b)) without increasing additional TS overhead. Because the channel information \( H_{\text{fine}} \) used in the OFDE stage is now highly accurate, data recovered from the OFDE are fully equalized and the second time CE and channel equalization as that in the CON-ZGI are no longer necessary.

### 2.2 Reduced computational complexity

In order to successfully tracking the time varying channel, the CSI updating speed should be at least faster than the CSI varying speed. Since the CSI information can be switched only between different OFDE frames, the upper bound of the updating speed would be feeding back the CSI information after every OFDE frame once the OFDE size is fixed. Due to the mismatch of the fast Fourier transform (FFT) size of the OFDE stage (~thousands) and of the
ZGI OFDM symbols (~hundreds), an accurate $\mathbf{H}_{\text{fine}}$ can be obtained from different $\mathbf{H}_{\text{coarse}}$ from data symbols demodulated from the current OFDE stage, and applied to the OFDE instantly to provide the latest CSI, which has the fastest converging and CSI tracking speed at the expenses of the highest complexity. In reality, since optical transmission fiber is a relatively slow-varying channel, the channel matrices could be updated just fast enough according to channel time varying rates to save some computational efforts, and the final computational complexity depends on the CSI updating speed and averaging length. Throughout this work, however, we only implement the former method for simplicity, i.e., the one with the fastest updating speed. In section 3.2, we will show this updating speed is more than enough in typical situations. However, considering the saved DSP blocks, although more efforts are being made to extract the latest channel information, the overall complexities of both CON-ZGI and Adaptive-ZGI systems are expected to be similar even with the fastest feedback speed. Indeed, from Fig. 2 we can see that the only difference between CON-ZGI and Adaptive-ZGI is that the latter one has an additional data-aided decision feedback block but one reduced CE block. Since the two blocks are essentially the reverse operation of each other, the two systems would have the same complexity. On the other hand, the overall complexity of Adaptive-ZGI would be even lower than that of the CON-ZGI if the updating speed is set to just accommodate the channel varying rate. But in Adaptive-ZGI, the channel matrix of the OFDE stage is adaptively updated quickly enough with a negligible TS overhead. More details of the ZGI CO-OFDM receiver DSP including channel equalization, frequency domain interpolation and channel coefficient updating method can be found in [5] and [6].

2.3 Benefits of Adaptive-ZGI

Two potential properties of the Adaptive-ZGI system could be inferred from the above system design. First, the Adaptive-ZGI combines the advantages of both ISFA and TA methods, i.e., the system could achieve an accurate CE, even in the presence of ISI, without decreasing the system SE. Second, since the Adaptive-ZGI is possible to update the CSI on an OFDE basis without increasing TS overhead, the system should perform well in time varying channels. We will justify both properties in the following sections.

The third potential benefit appears when we carefully examine the fiber nonlinear tolerance of the Adaptive-ZGI. Figure 3 shows the interplay between TS and data symbols during transmission. Due to fiber CD, different frequency components of a transmitted signal travel at different speeds. Therefore, different frequency components of the originally time aligned OFDM symbols overlap after transmission, which imposes an interaction between TS and data symbols. Because of the stochastic nature of data symbols (also means random interactions), performance results of systems that employ noise suppression method like ISFA that relies on only a pair of TSs also exhibit randomness. In addition, it is showed in [14] that fiber nonlinearity, especially self-phase modulation (SPM), has a great impact on the CE performance of OFDM systems. Specifically, SPM introduces a non-uniform nonlinear phase shift across TS’s different subcarriers if the power profile of the OFDM signal is non-flat. And because of the randomness of data symbols, there is a large possibility that different subcarriers of data symbols have non-uniform instant power. This implies that the interactions of different frequency portions between TS and data symbols are also non-uniform (denoted by the circles of different colors in Fig. 3), and leads to the aforementioned non-uniform phase shift across different subcarriers of TS. This TS induced additional nonlinear penalty is also observed in a recent publication for single carrier transmission system, where the nonlinearity is compensated with digital back propagation of the TS [15].
To prove the above inferences, we performed simulations with 100 different realizations of data symbols. For each realization, only the pseudo random binary sequence (PRBS) used for the generation of data symbols is changed while all the other parameters, including TS and noise seeds, remain the same. Simulation results are shown in Fig. 4. For the CON-ZGI, we can clearly observe the statistical distributions of the results that came from the random nature of data symbols. And from recovered constellations of one realization on the upper right side, it’s obvious that there is a residual phase shift between the first and last subcarriers. On the other hand, the Adaptive-ZGI exhibits both a smaller variance and a larger mean value of 0.6 dB compared to the CON-ZGI. The smaller variance comes from the fact that the performance of Adaptive-ZGI depends on the statistics of large data and tends to converge to the true value when other conditions remain unchanged. The larger mean value results from the elimination of residual phase shift, as shown in the constellation points on the lower right side. Because the residual phase shift is highly correlated among neighboring subcarriers but not so much between neighboring OFDM symbols, which can be observed from Fig. 3, the ISFA method used in the CON-ZGI is not as effective in averaging out the residual phase shift as the TA method used in the Adaptive-ZGI, and leads to the performance degradation. Although we observed that the CON-ZGI could also achieve similar Q factor as the Adaptive-ZGI with some certain TS and data set combinations, since the impairment is data dependent, it is difficult to design an optimized TS that works for all different sets of data.

3. Experimental setup and results

3.1 Experimental setup

A single channel 112 Gb/s PDM-QPSK ZGI CO-OFDM experiment was conducted to evaluate the proposed algorithm. Figure 5(a) shows the experimental setup. In the offline DSP at the transmitter, a data stream consisting of a PRBS of length $2^{18}$ was mapped to QPSK symbols on 111 subcarriers. One additional pre-emphasized pilot subcarrier was inserted for laser phase estimation [16]. Through the use of PEPS, the processing overhead for LPNC was
The only one PEPS was used to prevent phase ambiguity and to adaptively track the residual laser frequency offset. The DC subcarrier was unfilled to avoid DC leakage. 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. 8-samples CP was inserted for each TS and no CP was added to the data symbols. Limited by the FPGA memory length (2^18), 1500 OFDM symbols were used for the bit error rate (BER) calculation. Therefore, the total OFDM processing overhead (LPNC and CE) was only 1.03% (1/112 + 2.13/1500).

The time domain 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 bits resolution for the generation of the 28 Gbaud electrical OFDM signals. Optical IQ modulation was employed for the electrical to optical conversion. PDM signal was formed using the PDM emulator with a delay of 2176 samples in order to fully de-correlate the signal of the two polarizations. Unlike the experiment in [10] where only TSs are time aligned, this time we arranged the OFDM frame in the way as shown in Fig. 5(b). Through the insertion of CP for some additional data symbols, both the TSs and most of the data symbols can be time aligned after the PDM delay. However, the final BER was calculated only from data symbols without CP. After the transmitter, the signal amplified by a booster was then launched into a recirculating loop, which consisted of 4 spans each having 80 km standard single mode fiber (SSMF) and an erbium doped fiber amplifier (EDFA) with a claimed 5 dB noise figure. 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. Offline processing was started with front end correction and re-sampling to 32 Gs/s. Then the FFT window synchronization was achieved by calculating the cross-correlation of the training symbols and received signals [17]. The rest of the main procedures of the offline processing were performed as described in the previous sections.
3.2 B2B performance

Figure 6(a) shows the back to back (B2B) performance of the CON-ZGI and Adaptive-ZGI, respectively. For the CON-ZGI, there are two times ISFA based CE to be performed at the receiver. The first one is a small length ISFA \( L_1 \) aiming to remove most of the ISI at the OFDE stage. The second time is a large size ISFA \( L_2 \) enabling a fine channel estimation and equalization as that in conventional OFDM [5]. The overall system performance depends on the combinations of the two CEs. On the one hand, ISI induced penalty increases as \( L_1 \) goes larger. On the other hand, \( L_1 \) determines the upper bound of the accuracy of the second time CE, i.e., if \( L_1 \) is too small, even a very large \( L_2 \) cannot achieve a good performance. Therefore, there is a balance between different choices of \( L_1 \) and \( L_2 \). In the experiment, systems with various ISFA averaging lengths \( L = L_1 + L_2 \) are compared. It can be seen that the system with a total averaging length \( L = 10 \) (3 + 7) has a noticeable performance degradation compared to the system with \( L = 20 \) (7 + 13) and 30 (11 + 19). Further increasing \( L \) beyond 30 brings diminishing improvement in the performance but reduces the frequency resolution of the CE and increases the computational efforts [9]. Therefore, the maximum averaging length is set to \( L = 30 \) in this paper. It should be noted that the reason we can use such a large ISFA averaging length (e.g. \( L = 30 \)) in the experiment is because of the zero ISI in the B2B configuration. However, in a real system, there might be a stronger PMD and residual CD, which would limit the averaging length of ISFA (e.g. \( L \leq 10 \)) and induce a noticeable CE penalty, which we will show later.

For Adaptive-ZGI, the OFDE size in the experiment was set to 4096 with 512 overlapped samples. Therefore, enough OFDM symbol pairs \((4096-512)/128/2 = 14\) could be demodulated from one OFDE stage. In the experiment, the OFDM symbols recovered from the current OFDE are used to estimate a new channel response and feedback to the next OFDE frame instantly for simplicity, which has the fastest converging and tracking speed at the expenses of the highest computational complexity, as described above. In this situation, the CSI updating speed was \( 1.12 \times 10^{-7} \) samples \( s^{-1} \). It’s showed in [18] that optical channel usually changes in a sub-milliseconds time scale. Therefore, the updated information is still effective for the next around 3.2 \times 10^6 \) samples following the OFDE frame. This means the algorithm is also robust to potential latency with real implementations, e.g. induced by feedback process due to parallel block processing or computational speed.
limitation of the hardware. In reality, there is a maximum speed at which the condition of optical channel varies along with time. And the CSI updating frequency can be changed accordingly to reduce the complexity. In addition, due to the insertion of the TS used for CE initialization purpose, the proposed algorithm convergences at a very fast speed. In the experiment we observe that the algorithm typically gave an accurate estimation after just tens of symbols.

It is showed in Fig. 6(a) that the Adaptive-ZGI achieves a performance similar to CON-ZGI with \( L = 30 \) in B2B configuration, proving that Adaptive-ZGI has the same efficiency in reducing the additive white Gaussian noise (AWGN) as the CON-ZGI. And from Fig. 6(b), we can see that the constellations for both systems are at the correct locations since AWGN added by noise loading EDFA is the only source of the system impairments in the B2B conditions.

### 3.3 Improved residual CD tolerance

In the presence of residual CD, there is a large phase variation across the subcarriers and thus the frequency correlation of neighboring subcarriers varnishes [9]. From Eq. (2), we can see the ISFA process becomes inaccurate in such situations, especially for edge subcarriers, because: (1) edge subcarriers experience larger phase variations than central ones, and (2) the ISFA process is asymmetric for edge subcarriers. This problem is more severe for RGI and ZGI CO-OFDM than for conventional OFDM since each subcarrier occupies a much broader frequency bandwidth and the correlation of different subcarriers is much weaker. Figure 7(a) shows the measured Q factor penalty (derived from BER) after a 4800 km transmission when residual CD exists. Performance of the CON-ZGI with large ISFA sizes \( (L = 20 \) and 30) degrades quickly as the residual CD increases. On the other hand, CON-ZGI with a small ISFA size \( (L = 10) \) suffers from a ~0.8 dB penalty without any residual CD due to the insufficient averaging length, but it performs better for >3000 ps/nm residual CD than CON-ZGI with \( L = 20 \) and 30 because fewer subcarriers are affected by the asymmetrical averaging process. For the Adaptive-ZGI, however, a 5000 ps/nm residual CD only induces a penalty of less than 1 dB. Figure 7(b) shows the measured subcarrier Q factor of CON-ZGI and Adaptive-ZGI with 3000 ps/nm residual CD. We can observe noticeable Q factor degradations for edge subcarriers in CON-ZGI, but not for Adaptive-ZGI. Therefore, we justify the improvement of Adaptive-ZGI system in the presence of residual CD is due to the fact that the time averaging used in Adaptive-ZGI can get as accurate channel matrix for edge subcarriers as for central ones, and circumvents the aforementioned edge subcarriers performance degradations in CON-ZGI.

![Fig. 7. (a) Q factor penalty as a function of residual CD. (b) Q factor for each subcarrier with a 3000 ps/nm residual CD.](image-url)
3.4 Improved intra-channel nonlinearity tolerance

CO-OFDM system is generally considered to be more sensitive to fiber nonlinearities due to its high peak-to-average power ratio (PAPR). As mentioned in Section 2, the Adaptive-ZGI system has a potential fiber nonlinear tolerance advantage over the CON-ZGI system. Therefore, we conducted an experiment to study the intra-channel nonlinearity tolerance of the CE procedure in the Adaptive-ZGI system.

Figure 8(a) shows the Q factor (derived from BER) as a function of the launch power for the CON-ZGI and Adaptive-ZGI after a 4800 km transmission. It can be seen that the Adaptive-ZGI has a 0.5 dB Q factor improvement at the optimum fiber launch power (−1 dBm). We also noted that increasing the averaging length of CON-ZGI was not an effective way to mitigate the performance difference, which might be related to the relative amount of OFDM symbol size and CD induced walk off [14]. Figure 8(b) shows the recovered constellations of two different subcarriers (1st and 56th) for CON-ZGI and Adaptive-ZGI at the optimum launch power, respectively. Both of the two results are consistent with our former simulation results, meaning the SPM induced phase shift could be effectively ruled out by the TA method used in the Adaptive system. With the improved fiber nonlinear tolerance, from Fig. 8(c), the transmission distance of the Adaptive-ZGI reaches 5120 km at the BER threshold of 3.8E-3 at the optimum launch power, and is ~640 km longer than that of the CON-ZGI, giving a ~13% transmission distance improvement. It should be noted that the transmission distance improvement solely comes from the higher fiber nonlinearity tolerance of the Adaptive-ZGI since the fiber CD was perfectly compensated at the receiver and the PMD of our fiber is almost negligible.

![Figure 8](image-url)
4. Simulations and discussions

In order to further investigate the properties of the Adaptive-ZGI, we conducted several simulations to manipulate the impairments that are common in a real fiber communication system but are not precisely controllable in the experiment. Simulation parameters are adjusted such that the performance results are similar to those of our experimental setup.

4.1 Improved PMD tolerance

PMD is a major impairment for high-speed optical fiber transmission system, which also leads to frequency miscorrelations of neighboring subcarriers. Extensive simulations were conducted to investigate the robustness of the Adaptive-ZGI against fiber PMD. Since PMD is a stochastic phenomenon and the instantaneous DGD follows a Maxwellian distribution, we calculate the Q factor (derived from BER) for 500 different realizations for each <DGD> value. Figure 9 compares the Q factor distributions for CON-ZGI and Adaptive-ZGI CO-OFDM for three different <DGD> values of 0, 25 and 50 ps, respectively. The received OSNR is 14 dB. For simplicity, only $L = 30$ is considered for different PMD values. But the trends for different $L$ are the same as in the above section. As shown in Fig. 9, the CON-ZGI and Adaptive-ZGI have similar performance at <DGD> = 0 ps, which is consistent with the experimental results. However, a large performance penalty (~1.7 dB in the mean value of Q) of CON-ZGI appears when <DGD> is increased from 0 to 25 ps, even though only a ~0.2 dB additional penalty is observed when <DGD> is increased from 25 to 50 ps. For Adaptive-ZGI, on the other hand, only a 0.05 dB penalty is observed when <DGD> is increased from 0 to 50 ps. In addition, the variance of the Adaptive-ZGI is much smaller than that of the CON-ZGI. The reason for the performance improvement of the Adaptive-ZGI in the presence of a non-negligible PMD is similar to the explanation for performance with residual CD.

![Graph showing Q factor distributions for CON-ZGI and Adaptive-ZGI with different DGD values.](image)

Fig. 9. The distributions of the received Q factors as a function of <DGD> = 0 ps (upper row), 25 ps (middle row) and 50 ps (lower row) for CON-ZGI (left column) and Adaptive-ZGI (right column) at OSNR = 14 dB.
4.2 Improved channel variation tracking ability

Channel physical changes due to vibrations, manufacture imperfections, temperature and other environmental factors cause the rotation of the state of polarizations in fiber optical transmission systems. It’s shown in [18] that polarization states can change in the sub-millisecond time scale in regular fiber links. Therefore, we conducted numerical simulations to assess the performance of the Adaptive system in the presence of SOP rotation.

Figure 10 shows the Q factor penalty (derived from BER) for CON-ZGI and Adaptive-ZGI when a continuous SOP rotation is applied to the channel. For CON-ZGI, we can see the Q factor penalty increases as the frame length (FL) increases. Systems with a smaller FL have a better ability to accommodate fast drifting effects at the expense of an increased overhead. The performance of the Adaptive-ZGI is close to CON-ZGI with FL = 50 (4% overhead), with a negligible penalty in regular fiber links (<0.4 dB for < 100 kHz SOP rotation speed) [18].

![Fig. 10. Q factor penalty as a function of the SOP rotation speed (OSNR = 14 dB).](image)

4.3 Improved SFO tolerance

Sampling frequency offset between the transmitter and receiver has three effects on CO-OFDM systems: (1) ISI between neighboring OFDM symbols, (2) a time and frequency dependent phase shift on transmitted quadrature amplitude modulation (QAM) symbols, and (3) inter-carrier interference (ICI) due to the loss of orthogonality between subcarriers [19]. In practice, even a small amount of SFO seriously degrades the OFDM system performance. In typical OFDM systems, SFO is first estimated and then corrected based on the estimated value. However, a more or less estimation error is usually inevitable depending on the estimation methods and the system OSNR [7,19]. Numerical simulations were performed to investigate the tolerance of the Adaptive-ZGI to SFO estimation errors. In the simulation, a standard SFO of 200 ppm is applied to the received signal and the basic time domain digital interpolation method is used for SFO compensation [19]. Figure 11 shows the Q factor penalty (derived from BER) of the CON-ZGI and the Adaptive-ZGI in the presence of the SFO estimation error, respectively. For CON-ZGI, similar to the time varying situations, systems with shorter frame length suffers less from the estimation error at the expense of the reduced SE. At 1 dB Q factor penalty, CON-ZGI can tolerate only 1%~2% SFO estimation error depending on the frame length. Adaptive-ZGI, however, can tolerate up to 9% estimation error with a negligible TS overhead at a 1 dB Q factor penalty. Thus the Adaptive-ZGI system is highly robust against the SFO estimation errors.
Fig. 11. Q factor penalty as a function of the SFO estimation error @ standard 200 ppm (OSNR = 14 dB).

5. Conclusion

In this paper, we presented and experimentally demonstrated a decision feedback channel estimation algorithm for ZGI CO-OFDM. In a single channel 112 Gb/s experiment, the maximum transmission distance can be extended by 13% using the adaptive channel estimation algorithm with only 1.03% processing overhead at the BER threshold of 3.8E-3. In addition, we systematically investigated its robustness against various transmission impairments such as residual CD, PMD, SOP, SFO, and intra-channel fiber nonlinearity. Both numerical and experimental results proved that the adaptive channel estimation algorithm is highly robust against the above typical impairments encountered in fiber optical transmission system.