Reduced-Guard-Interval CO-OFDM with Overlapped Frequency-Domain CD and PMD Equalization

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Abstract: We propose an algorithm for CO-OFDM receivers to perform overlapped frequency-domain CD and PMD equalization before OFDM symbol demodulation. This approach enables OFDM transmission with a small cyclic prefix overhead of only 0.08%, and can enlarge the frequency averaging length for channel estimation in the presence of high PMD.

I. Introduction

Coherent orthogonal frequency-division multiplexing (CO-OFDM) has emerged as a promising solution for next-generation long-haul optical transmission [1-3]. A guard interval (GI), in term of cyclic prefix (CP), is inserted between adjacent OFDM symbols as a convenient means to avoid inter-symbol interference (ISI) due to fiber chromatic dispersion (CD) and polarization mode dispersion (PMD). However, CP increases system overhead and limits the minimum FFT size for OFDM symbols, and the latter tends to increase system's vulnerability to laser phase noise and fiber nonlinearities [4]. This paper presents a new equalization scheme to reduce the CP overhead for polarization-division-multiplexing (PDM) CO-OFDM transmission. Our scheme employs an overlapped frequency domain equalizer (OFDE) [5] to compensate both CD and PMD using the channel estimation obtained from the training symbols (TS's). This approach enables a significant reduction in CP overhead and increase in the intra-channel spectral efficiency for OFDM transmission. Specifically, we demonstrate a 112-Gb/s PDM CO-OFDM transmission with a CP overhead of only 0.08%. Compared to conventional [1-2] and the previous OFDE-based RGI [3] CO-OFDM systems, where the CP overhead is ~10% and 3.13%, respectively, the CP overhead in our system is negligibly small. We achieve a total system overhead of only 3% (excluding FEC and Ethernet related overhead). Additionally, this new scheme can achieve a larger PMD tolerance, and improve channel estimation accuracy by enlarging the intra-symbol frequency averaging (ISFA) length [6], compared to a recently demonstrated reduced-GI (RGI) CO-OFDM system [3]. Finally, this approach enables to use a small FFT size of <128 for OFDM transmission while keeping a small CP overhead.

II. Operation principle

Various approaches to reduce CP overhead have been explored in previous work [3, 5, 7]. Recently a RGI CO-OFDM was demonstrated to operate with a small FFT of 128 and a small CP overhead of 3.13% [3]. This system used an OFDE to compensate CD before OFDM demodulation, so that CP can be reduced to only a few samples to compensate ISI from PMD and transmitter bandwidth limitation [3]. The scheme proposed in this work represents one step further, which enables the OFDE to compensate both CD and PMD, thus further reducing CP. Fig. 1(a) illustrates the CO-OFDM receiver structure in this work. Besides performing CD compensation, the key feature of the OFDE here is to acquire the channel estimation (in form of a 2*2 matrix *H(k)* for each of the k^{th} modulated subcarrier) after the OFDM demodulator has processed the TS's, and then compensate PMD by applying the inverse of the channel matrix. With both CD and PMD compensated at the OFDE, subsequent data symbols can be transmitted with a very small CP. Fig. 1(b) shows the OFDM frame used in this work. While a small CP is required for TS's for accurate channel estimation, an even smaller CP is allocated for data symbols. Similar to [3], we use 4 TS's for every 300 data symbols with a FFT of 128 for synchronization and channel estimation. Each TS and data symbol contains a CP length of 4 and 1, respectively, producing a CP overhead of 0.08% (=1/128). 56-Gb/s data are encoded on the 80 QPSK-modulated subcarriers (including one pilot subcarrier for laser phase compensation) for each polarization. The overall system overhead is 3%, summing the overheads from CP, TS and pilot subcarrier.

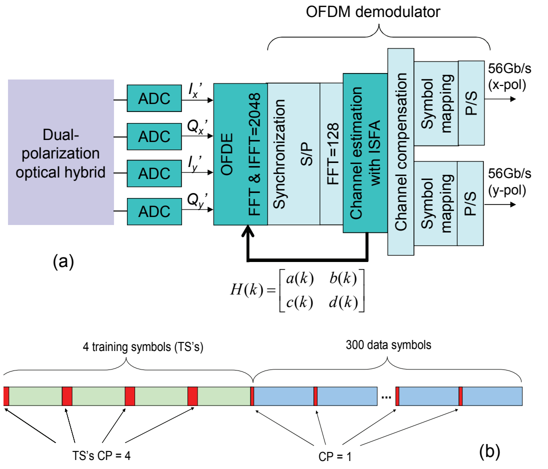

Fig. 1: (a) CO-OFDM receiver structure and (b) OFDM frame

In our new scheme, we perform the channel estimation and equalization with the following steps,

1. At OFDE, apply CD compensation to the received TS's (t_1 and t_2), and produce t_1' and t_2'
2. At OFDM demodulator, estimate the channel matrix H for each modulated subcarriers from t_1' and t_2'. ISFA can be applied, and the averaging length depends on PMD.
3. OFDE acquires H, and performs frequency-domain interpolation (FDI) to map H to H'.
4. OFDE applies both CD compensation and the inverse of channel matrix (H'^{-1}) to the received TS's (t_1 and t_2), and produce t_1'' and t_2''
5. At OFDM demodulator, estimate the channel matrix H'' from t_1'' and t_2''. A large ISFA length can be used to improve channel estimation accuracy, as CD and PMD are compensated at (4). H'' will be used for the subsequent data symbols.

Different from the channel estimation and compensation in previous CO-OFDM systems, our scheme relies on a collaborative effort between the OFDE and OFDM demodulator, and it requires processing the same TS and performing channel estimation twice. It is important to note the FFT sizes for the OFDE and OFDM symbols are different [3, 7]. Specifically in our system the OFDM symbols have a FFT size of 128, but the OFDE uses a FFT size of 2048 and overlapped sample number of 512. Therefore at Step (3), it is necessary to perform FDI with an interpolation factor equal to the ratio of two FFT sizes. In Fig. 2(a) the open circles indicate the channel matrix H, and the curve connecting the circles results from FDI. Fig. 2 assumes TS's have 64 modulated subcarriers, so that the OFDM signal power concentrates within the center half of the FFT length. At Step (4) the channel matrix H' after FDI is multiplied to the OFDM signal within this center half, which removes PMD from the OFDM signal. In Fig. 2(b) and (c) we assume a deterministic differential group delay (DGD) of 320 ps. The open dots on the top curve in Fig. 2(b) shows the real part of a from 64 channel matrices H (see Fig. 1), and the curve connecting the dots results from FDI. The periodicity of the curve is inversely proportional to DGD, and it would become irregular when considering higher-order PMD [6]. Therefore, in order to compensate a large DGD, one can increase TS's FFT size to ensure a fine frequency resolution before FDI. Finally, Fig. 2(c) illustrates the phase variations across the modulated subcarriers on both polarizations before and after Step (4). Before Step (4), the phase linearly varies across the subcarriers due to a deterministic DGD of 320 ps. After Step (4), the phase variations approach to zero, indicating a successful PMD compensation.

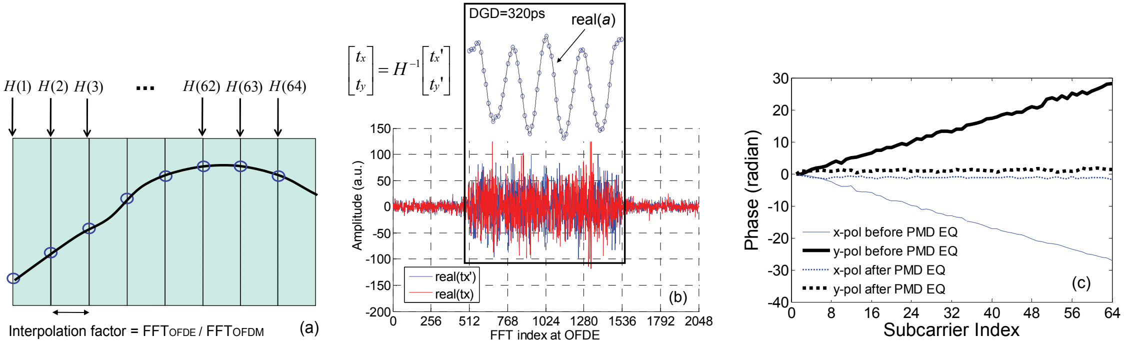

Fig. 2: (a) Schematic of frequency-domain interpolation (FDI). (b) OFDM spectrum before and after applying the inverse of channel matrix H'. The top curve shows the real part of a in the channel matrix H (open dot) and its interpolation (thin line). (c) Phase variations across modulated subcarriers before and after PMD compensation at Step (4).

III. System performance

In this work, a 112-Gb/s PDM CO-OFDM system is numerically studied using OptiSystem and Matlab. The transmission link consists of 1600-km (20 spans of 80-km) single-mode fiber (SMF) without optical dispersion compensation. The SMF has an attenuation of 0.2 dB/km and dispersion of 16 ps/nm/km. Besides CD, the overlapped sample size of 512 is sufficient to support a large DGD of ~2000 ps. Both transmitter and local oscillator lasers have a linewidth of 100 KHz. The launch power is fixed at -6 dBm to avoid significant fiber nonlinearities. Fig. 3(a) compares the received signal Q factor as a function of deterministic DGD's for three different CO-OFDM systems. The same ISFA length of 5 (i.e. m=2) and an OSNR of 14.5 dB are kept in Fig. 3(a) for comparison, although a larger Q may be achieved with a larger m for some DGD's. Despite a small CP overhead of 0.08%, the new scheme (Scheme A) achieves a large Q until a DGD of ~240 ps, indicating PMD being compensated before OFDM demodulation. Note that CP of one sample is used in data symbols to avoid any residue PMD. The Q rolls off as DGD increases above 240 ps, because TS's lose estimation accuracy as the PMD-induced ISI becomes significant. In contrast, the previous OFDE-based OFDM system (Scheme B) shows a limited PMD tolerance of ~70 ps that is consistent with [3] and its Q degrades drastically as DGD further increases. Fig. 3(a) also shows that although a conventional CO-OFDM without the OFDE (Scheme C) yields the best DGD tolerance, a large FFT size of 2048 and large CP overhead of 25% have to be used [4].

Furthermore, PMD is a time-varying stochastic process and can extend to higher-order in practice, thus it needs to be estimated and compensated periodically using TS's. To demonstrate Scheme A's ability to compensate PMD dynamically, 500 different fiber realizations are simulated with a mean DGD of 50 ps. Fig. 3(b) and (c) shows the Q factor distribution using Scheme A and B, respectively. Scheme A shows a better PMD tolerance, as its Q has a smaller variance against fiber variations. Note that Q is calculated using 300 data symbols in each OFDM frame. With Scheme B, however, a Q penalty occurs whenever the instantaneous DGD exceeds the system's prescribed PMD tolerance of ~70 ps. The Q distributions in Fig. 3(b) and (c) are consistent with our observation from Fig. 3(a).

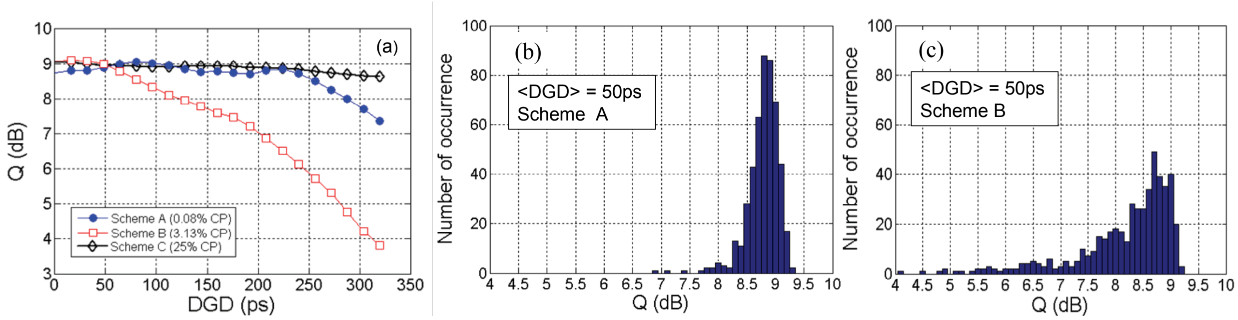

Fig. 3: (a) Q vs. deterministic DGD for three different CO-OFDM systems. Q factor distribution after transmission over a fiber link with 500 different PMD for Scheme A (b) and B (c).

Furthermore, Fig. 4(a) compares Q as a function of ISFA length m. In previous CO-OFDM systems, m to maximize Q is upper-bounded by the amount of residue CD or PMD [6]. This worsens for RGI CO-OFDM systems (e.g. Scheme A and B), where the m upper bound is 16x smaller compared to the conventional systems. Fig. 4(a) shows that with Scheme B, increasing m beyond its bound will result in Q degradation and the same effect was observed in a conventional CO-OFDM system [8]. Only for a small DGD (<50 ps), $m>6$ can be used to achieve nearly ideal channel estimation and an optimal Q [6]. However, Scheme A can eliminate this drawback because the residue CD and PMD are approximately zero after the OFDE. Therefore, a larger m can be applied to achieve an optimal Q. When the DGD is 100 ps, the best Q achieved with Scheme A is 1 dB higher than that with Scheme B. Finally, Scheme A enables the use of even smaller FFT sizes (e.g. <128) while keeping a small CP overhead. In Fig. 4(b) Q decreases with decreasing FFT size and increasing DGD. This is expected as discussed earlier, for a given DGD, a smaller FFT will result in a coarser frequency resolution at the OFDE, limiting the PMD compensation ability. We can optimize the TS and OFDM frame to circumvent this limitation in the future.

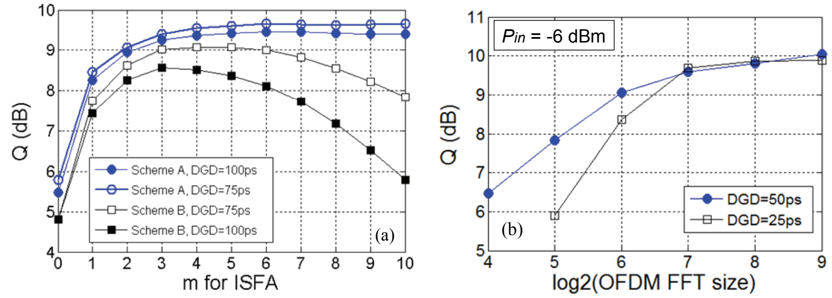

Fig. 4: (a) Q vs. ISFA length m using Scheme A and B and (b) Q vs. FFT size for OFDM symbols for two different DGD's.

IV. Summary

We present a novel scheme to compensate PMD before CO-OFDM demodulation. This scheme leads to the system benefits of (1) significantly reducing CP overhead (2) enlarging ISFA length to achieve higher Q, and (3) enabling OFDM transmission with a FFT size smaller than 128.

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References:

[1] S. L. Jansen, I. Morita, T. C. W. Schenk and H. Tanaka, *J. of Lightwave Tech.*, **27**, 177-188 (2009).
[2] Y. Qi, T. Yan, M. Yiran and W. Shieh, *J. of Lightwave Tech*, **27**, 168-176 (2009)
[3] X. Liu, S. Chandrasekhar, B. Zhu, P. J. Winzer, A. H. Gnauck, and D. W. Peckham, OFC 2010, San Diego, USA, PDPC2
[4] S. L. Jansen, B. Spinnler, I. Morita, S. Randel, and H. Tanaka, *Optical Fiber Technology*, **15**, 407-413 (2009).
[5] R. Kudo, T. Kobayashi, K. Ishihara, Y. Takatori, A. Sano and Y. Miyamoto, *J. of Lightwave Tech.*, **27**, 3721-3728 (2009).
[6] X. Liu and F. Buchali, *Optical Express*, **16,** 21944-21957 (2008).
[7] L. Du and A. Lowery, ECOC 2010, Vienna, Austria, Tu4A5
[8] Q. Yang, N. Kaneda, X. Liu and W. Shieh, *Photon. Technol. Lett.*, **21**, 1544-1546 (1999).