Impact of Polarization-mode Dispersion on Wavelet Transform Based Optical OFDM Systems

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Abstract: The impact of PMD on wavelet transform based optical OFDM (WTO-OFDM) systems is investigated. Simulations show that WTO-OFDM is very sensitive to PMD. A 1-dB penalty at 5-ps DGD is incurred for 112-Gb/s dual-polarization transmission.
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1. Introduction

Orthogonal frequency-division multiplexing (OFDM), widely studied as an efficient modulation technology for the wireless and wired systems in RF domain, has recently attracted significant interest from optical communications community [1-2]. In coherent optical OFDM (CO-OFDM) systems, by appropriately choosing the length of cyclic prefix (CP), both inline chromatic dispersion (CD) and polarization-mode dispersion (PMD) can be fully compensated via digital signal processing (DSP). This provides simplicity for optical network installation and reconfiguration. Wavelet transform, or wavelet packet transform (WPT) in particular [3], is a nascent technique in communications by which a signal is expanded in an orthogonal set called "wavelets". There is an incentive to use WPT in OFDM to provide better spectral roll-off and remove the need of a cyclic prefix, and wavelet transform based optical OFDM (WTO-OFDM) has been proposed as an alternative approach to conventional Fourier transform (FT) based OFDM (FTO-OFDM) [4]. It was shown in [4] that WTO-OFDM can mitigate a CD of 3,380 ps/nm at 112 Gb/s, a remarkable performance without requiring the cyclic prefix. However, the report in [4] is based on single-polarization systems. Since dual-polarization transmission has been recognized as a promising technique for future 100 Gb/s Ethernet transport [5-9], it is of great importance to study the system performance of dual-polarization WTO-OFDM under the influence of PMD. In this paper, we discuss the PMD impact on WTO-OFDM systems. We first introduce theoretically some fundamentals of WTO-OFDM and point out its potential deficiency when applied in the optical channel. Then we assess the impact of PMD on WTO-OFDM transmission with various commonly used wavelets, and comparison is drawn between WTO-OFDM and conventional FTO-OFDM. We find that WTO-OFDM is very sensitive to PMD, incurring 1 dB penalty at 5 ps of differential-group-delay (DGD) as opposed to 76 ps for conventional FTO-OFDM without cyclic prefix, both at the data rate of 112 Gb/s. Finally, we point out that using complex wavelets may be one solution to the problem of PMD sensitivity.

2. Theory of WTO-OFDM in the presence of PMD Effect

Wavelets are predominantly real-valued designed to process real signals such as patterns and images [10]. However for the fiber optic channel, whether the input signal is modulated by real or complex signal, the up-conversion to the optical domain will inevitably generate two spectral sidebands - one positive and the other negative. Fig. 1 shows the spectrum of Daubechies 32 (db32) wavelet [10], a typical wavelet with positive and negative sidebands. In order to evaluate the PMD impact on WTO-OFDM systems and compare with FTO-OFDM counterpart, we use the model of CO-OFDM transmission in a 2x2 multiple-input multiple-output (MIMO) representation [9]. The received OFDM symbol in a form of Jones vector for the *i*th OFDM symbol on the *k*th subcarrier can be written as [9]

$$\mathbf{r}(k,i) = e^{j\phi_i} e^{j\Phi_D(f_k)} \mathbf{T}(k)\mathbf{c}(k,i) + \mathbf{n}(k,i) \qquad (1)$$

where $\mathbf{c}(k,i)$ is the transmitted symbol as a Jones vector and $\mathbf{n}(k,i)$ is the corresponding received noise vector. ϕ_i is the OFDM symbol dependent phase noise. Phase dispersion due to fiber chromatic dispersion (CD) is given by

$$\Phi_D(f_k) = \pi c D f_k^2 / f_{LD}^2 \qquad (2)$$

For simplicity, we use the commonly-used first-order PMD approach for which the Jones matrix for the fiber link on the *k*th subcarrier can be modelled as

$$T(k) = M^{-1} \begin{bmatrix} e^{-j\pi f_k \tau} & 0 \\ 0 & e^{j\pi f_k \tau} \end{bmatrix} M \text{ , } M = \begin{bmatrix} \cos(\theta/2) e^{-j\psi/2} & -\sin(\theta/2) e^{-j\psi/2} \\ \sin(\theta/2) e^{j\psi/2} & \cos(\theta/2) e^{j\psi/2} \end{bmatrix} \qquad (3)$$

where τ is the DGD of the link, θ and ψ are the polar and azimuth angle of the principle state of polarization (PSP) respectively, and f_k is the subcarrier frequency. In FTO-OFDM systems, the individual subcarrier, as the orthogonal basis of the Fourier transform is single-sideband by nature, $\Phi_D(f_k)$ in (2) and $T(k)$ in (3) can be conveniently estimated and compensated. In contrast, in WTO-OFDM systems, the modulated signals are double-sideband by nature (see Fig. 1). By applying theory similar to Eqs.(1)-(3), chromatic dispersion influence on WT-OFDM is benign because the two sidebands experience equal phase dispersion $\Phi_D(f_k) = \Phi_D(-f_k)$. However PMD does not hold such phase symmetry. The Jones matrixes for the positive and negative sidebands do not equal, i.e. $T(k) \neq T(-k)$. Upon reception where the two sidebands need to be recombined and projected onto real wavelet basis, the two sidebands experience two different dispersions, and the addition of the two does not reproduce the real-wavelet basis, resulting in violation of the orthogonality and therefore inter-packet-interference. This is illustrated in Fig. 2 where the conceptual figure of PMD impact on OFDM subcarriers in one polarization launch is shown. We conclude that WTO-OFDM will be more susceptible to PMD than conventional FTO-OFDM.

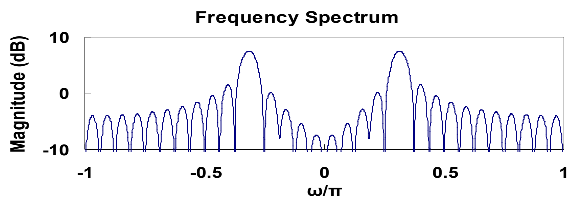

Fig. 1 Spectrum of one db32 wavelet packet, constructed using 5-level IDWPT.

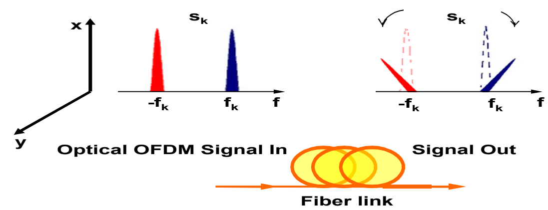

Fig. 2 Illustration of PMD impact on *k*th wavelet packet in WTO-OFDM systems for x polarization component.

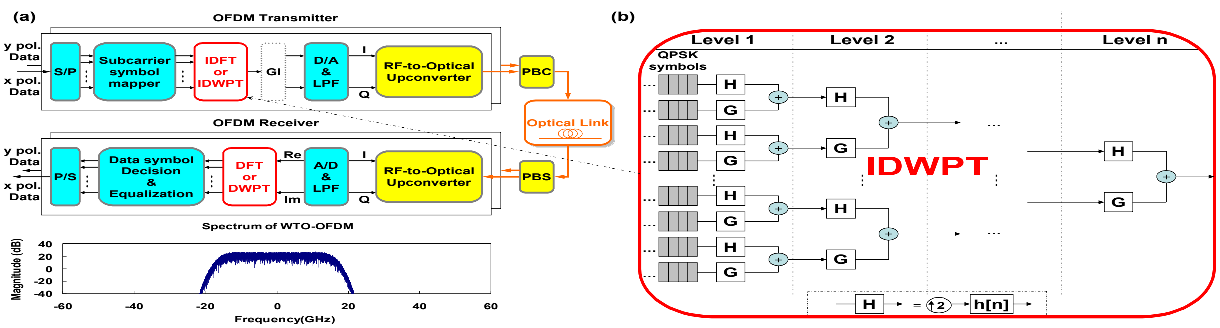

Fig. 3 Conceptual diagram of WTO (FTO)-OFDM system. (a) OFDM system setup. For WTO-OFDM, IDWPT and DWPT are used as a pair, and for FTO-OFDM, IDFT and DFT are used as a pair. PBC/PBS: Polarization Beam Combiner /Splitter, LPF: Low Pass Filter. (b) Tree-structure of IDWPT function block. The inset to the bottom left is the optical spectrum of 112-Gb/s WTO-OFDM signal.

3. Simulation of 112 Gb/s WTO-OFDM transmission

We have carried out numerical simulation to compare the transmission performance of dual-polarization WTO-OFDM systems with FTO-OFDM systems. The simulation parameters are: dual-polarization OFDM data rate at 112 Gb/s, 64 subcarriers oversampled by a factor of 2 to avoid aliasing. Fig. 3(a) shows the signal flow of a typical WTO-OFDM system used in simulation. At the transmitter, the serial PRBS at 56 Gb/s is converted into 64 parallel data pipes, mapped onto the complex plane in QPSK modulation, each corresponding to the wavelet coefficient in frequency domain. The wavelet coefficients are converted into serial time-domain wavelet signal through inverse discrete wavelet packet transform (IDWPT). The detailed IDWPT tree structure consisting of n-level 'high' and 'low' quadrature-mirror-pair finite impulse response (FIR) filters (h[n] and g[n]) is shown in Fig. 3(b). The "leaves" to the most left are the one-to-one mappings to the OFDM packets. H (or G) stands for operation of 2 times up-sampling, followed by convolution with synthesis high-pass filter h[n] (or low-pass filter g[n]). The high- and low-pass branches are then summed up generating a new sequence. After n-level of such iterative processes, the "root" to the most right gives the time-domain transformed data. The prominent difference between IDWPT and IDFT is that IDWPT is not block based, and therefore does not need a cyclic prefix. The wavelet signal is then up-converted onto an optical carrier with central frequency at 193.1 THz using an ideal optical I/Q modulator. The two 56-Gb/s optical signals are polarization combined into a 112-Gb/s WTO-OFDM signal and launched into the optical fiber. The inset in Fig. 3(a) shows the optical spectrum of WTO-OFDM signal with a bandwidth of 28 GHz. The WTO-OFDM signal is then passed through a fiber with chromatic dispersion and PMD. At the receiver, the WTO-OFDM signal is coherently down-converted to the RF domain, sampled and transformed back from time to frequency domain through DWPT, followed by the channel equalization, symbol decision, and bit-error-ratio (BER) computation. 10 training symbols with alternative polarization launch is sent for channel estimation. A one-tap equalizer is introduced for equalization of CD and PMD at the receiver [9]. In all simulation and analysis for the PMD impact, we have assumed that the signal on each polarization is launched 45^o with respect to the PSP of the PMD for which we find the worst penalty takes place.

Fig. 4 shows the BER performance versus optical signal-to-noise ratio (OSNR) at 0 and 10 ps of DGD with different family of wavelets for a 112-Gb/s WTO-OFDM signal. The naming convention of the wavelet is its family name followed by the order. The OSNR penalty as a function of DGD for the same family of wavelets are analysed and the results are shown in Fig. 5. It can be seen that the DGD tolerance for 1 dB OSNR penalty is 11, 6, 5, and 5 ps for Haar, Coifilet5, Daubechies32, and Johnston64(E) wavelets [10,11], respectively. The performance of OSNR penalty versus DGD for FTO-OFDM is shown in Fig. 6, indicating 76 and 93 ps DGD can be tolerated for FTO-OFDM systems with and without CP respectively. Consequently, the PMD tolerance of FTO-OFDM is more than six times higher than that of WTO-OFDM systems. By using sufficiently long CP, the PMD penalty can be greatly improved and even completely eliminated in FTO-OFDM systems [9]. We also perform the simulation to study the PMD tolerance dependence on the number of subcarriers for WTO-OFDM and result is presented in Fig. 6. It can be seen that for WTO-OFDM systems, almost no improvement can be gained by increasing the number of subcarriers. This is because that the double-sideband characteristics of WTO-OFDM spectrum will always adversely affect the PMD performance, irrespective of how finely each wavelet is being partitioned.

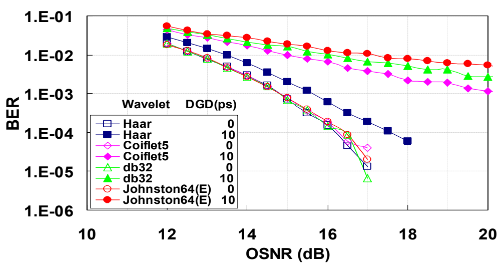

Fig. 4 BER vs. OSNR for WTO-OFDM without DGD(0ps) and with DGD(10ps). Wavelets are from Haar, Coiflet, Daubechies [10] and Johnston [11] family. Number of subcarriers Ns = 64.

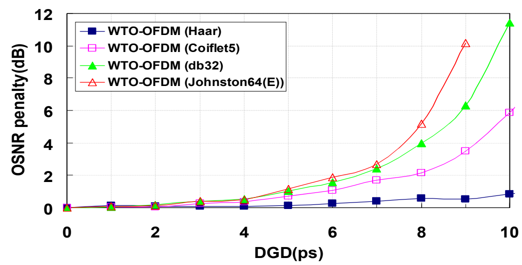

Fig. 5 OSNR penalty vs. DGD for WTO-OFDM. Wavelets are from Haar, Coiflet, Daubechies and Johnston family. Number of subcarriers Ns = 64.

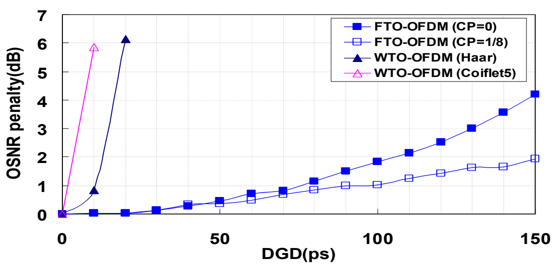

Fig. 6 OSNR penalty vs. DGD for FTO-OFDM without CP and with CP of 1/8. Number of subcarriers Ns = 64.

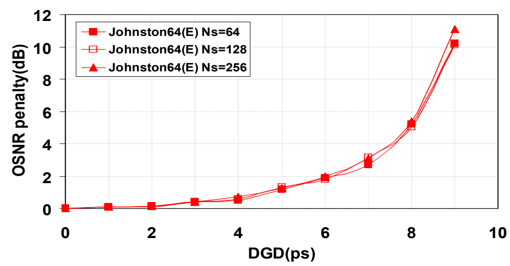

Fig. 7 OSNR penalty vs. DGD for WTO-OFDM using Johnston wavelet with varying number of subcarriers.

In order to solve this problem of PMD sensitivity, one natural way is to generate single-sideband wavelets in frequency domain. Similar to the Fourier transform that is based on complex-valued oscillating sinusoids, specifically designed complex wavelets with complex-valued scaling function and wavelet function $\psi_c(t) = \psi_r(t) + j\psi_i(t)$ can also have the single-sideband characteristics if $\psi_r(t)$ and $\psi_i(t)$ form a Hilbert transform pair [12]. This 'simple' solution leads us to a path searching for a complex wavelet suitable for use for optical fiber channel. Unfortunately, complex wavelet by itself is a relatively new field [12] and its adaptation into optical communications remains an open question, which we will explore in our future work.

4. Conclusions

The impact of polarization-mode dispersion (PMD) on wavelet transform based optical OFDM (WTO-OFDM) systems has been analysed. We have shown that WTO-OFDM is very sensitive to PMD.

References

[1] W. Shieh, et al., Electron. Lett., 42, 587-588, 2006.
[2] A. J. Lowery, et al., OFC'2006, Paper PDP39.
[3] R. Coifman et al., "Signal processing…", Yale Univ., 1990
[4] Ömer Bulakci et al., OFC'2009, Paper OTUO6.
[5] S. J. Savory, et al., Opt. Express 15, 2120-2126, 2007.
[6] E. Yamada, et. al., OECC'2008 , Paper PDP6.
[7] H. Sun, et al., Opt. Express 16, 873-879, 2008.
[8] X. Liu et al., Opt. Express 16, 21944-21957, 2008.
[9] W. Shieh, et al., Opt. Express 15, 9936-9947, 2007.
[10] I. Daubechies, SIAM Publications, 1992.
[11] J. D. Johnston, ICASSP '80, pp. 291-294, 1980.
[12] I. W. Selesnick et al., IEEE Signal Processing Magazine, 2005