

Wavelet Transform Based Optical OFDM

Ömer Bulakci (1), Matthias Schuster (2), Christian-Alexander Bunge (2),
Bernhard Spinnler (3), Norbert Hanik (4)

1: Student at Technische Universität München, Dept. of Electr. Engineering & Inf. Technology, Munich, Germany, omer.bulakci@mytum.de

2: Fachgebiet Hochfrequenztechnik, Technische Universität Berlin, Berlin, Germany, matthias.schuster@tu-berlin.de

3: Nokia Siemens Networks GmbH & Co. KG, COO, IP Transport, Munich, Germany, bernhard.spinnler@nsn.com

4: Technische Universität München, Dept. of Electr. Engineering & Inf. Technology, Munich, Germany, norbert.hanik@tum.de

Abstract: Wavelet transform based OFDM is proposed to increase the dispersion tolerance of optical OFDM. For moderate accumulated dispersion the performance is shown to be comparable with Fourier transform based optical OFDM with 10% cyclic prefix.

© 2009 Optical Society of America

OCIS Codes: (060.2360) Fiber optics links and subsystems; (060.4080) Modulation

1. Introduction

Orthogonal frequency-division multiplexing (OFDM) is a promising modulation technique well known from wireless and wired communications, which recently has also been discussed for optical communications. A major reason is that it can be designed to be extremely tolerant to chromatic dispersion (CD) [1,2]. Another main advantage is its high flexibility as for example the data rate can be adapted easily to the available OSNR [3]. Conventional OFDM implementation utilizes Fourier transform as the orthogonal transform to generate the signal waveform from densely spaced low-rate subcarriers. These subcarriers are orthogonal, which is the key feature of OFDM to prevent inter-carrier interference (ICI). As sinusoids are infinitely long in time domain, a proper windowing has to be applied, which consequently causes out-of-band radiation in frequency domain and performance degradation on dispersive channels because of inter-symbol interference (ISI) [4]. In order to prevent ISI due to CD, a cyclic prefix (CP) can be appended to each OFDM block, which increases the tolerance to CD significantly. However, the addition of CP imposes an increase in required bandwidth and sampling rate of DA/AD-converters which are already at their limits for high data rates.

In lieu of Fourier transform, the orthogonality of the subcarriers can also be satisfied via wavelet transform, another orthogonal transform whose basis functions are wavelets rather than sinusoids. Wavelets have finite length in time domain and can be designed to have high frequency localization. Wavelets exist for different applications such as data compression and signal denoising. Besides, new wavelets can be designed according to specific requirements. Wavelet transform belongs to the family of overlapped transforms, i.e. the beginning of a symbol is transmitted before the previous one ends. The inter-symbol orthogonality is maintained due to the shift orthogonal property of the waveforms [5]. This overlapping feature increases the symbol duration and hence yields a better spectral containment along with higher CD-tolerance. On the other hand, because of the overlapping of the symbols in time domain, CP is not available for wavelets.

In this paper, the performance of wavelet transform based optical OFDM (WTO-OFDM) based on several wavelets available today is analyzed and compared to Fourier transform based optical OFDM (FTO-OFDM). First, the performance of WTO-OFDM is compared to FTO-OFDM without CP for a fixed signal configuration. Then, for a fair comparison, the performance is evaluated with respect to computational complexity. Here, for FTO-OFDM also 5% and 10% CP are considered.

2. WTO-OFDM Implementation

A wavelet is an oscillatory waveform $\psi(t)$, satisfying certain mathematical conditions [6]. $\psi(t)$ is non-zero for a limited period of time, hence does not need to be windowed. Wavelet transform performs signal analysis by means of scaled and translated versions of a so called mother wavelet $\psi(t)$, whereas Fourier transform analyzes signals by means of sinusoids of high and low frequencies. Similar to FTO-OFDM implementation, WTO-OFDM implementation employs inverse wavelet transform to map parallel input data onto N orthogonal subcarriers. In particular, IFFT at the transmitter and FFT at the receiver of FTO-OFDM are replaced by inverse wavelet packet transform (IWPT) and wavelet packet transform (WPT) for WTO-OFDM. WPT can be efficiently computed by a perfect reconstruction filter bank using finite impulse response (FIR) filters named quadrature mirror filters (QMFs), which is known as fast wavelet transform (FWT) [7]. FWT decomposes the signal into different frequency bands by means of successive low-pass and high-pass filtering in the time domain. The basic block, which is the fundamental computational infrastructure that is used to construct the whole filter bank, and the block diagram of IWPT for a system with $N=4$ subcarriers constructed using the basic block are shown in Fig. 1. In a basic block, after

upsampling by a factor of two at each branch, high-pass filtering is done by the half-band high-pass QMF $g[n]$ and low-pass filtering is done by the half-band low-pass QMF $h[n]$. The QMFs are interdependent and for the forward transform the time reversed versions, i.e. $g[-n]$ and $h[-n]$ are used. The number of subcarriers N is determined by the number of levels m as $N=2^m$. Therefore, the knowledge of m and the coefficients of any of the QMFs are sufficient for the implementation of the transform. The overlapping feature of WTO-OFDM both in time and frequency domain is illustrated in Fig. 1a. This feature enables another degree of freedom in addition to the number of subcarriers compared to FTO-OFDM; the symbol duration can be controlled by the QMF impulse response. Besides, for longer QMFs the spectrum of each subcarrier becomes steeper, which results in further increase in CD-tolerance.

3. Complexity Estimation of FTO-OFDM and WTO-OFDM

As the complexity measure, the total required number of complex multiplications is considered. For FTO-OFDM, the complexity of FFT is known to be

$$C_{FFT} = N \cdot \log_2(N). \quad (1)$$

For WTO-OFDM, the total complexity can be calculated starting from the complexity of a basic block. In one basic block the complexity is $C_{BB}=L$ due to convolutions between complex input data and real QMFs, given L as the QMF length. In an N -subcarrier filter bank there are $N-1$ autonomous basic blocks. Hence, the complexity of WPT is

$$C_{WPT} = (N-1) \cdot L. \quad (2)$$

On the other hand, oversampling is applied in signal generation to achieve tighter spectral control of the OFDM signal and to avoid aliasing. Oversampling is also important in complexity calculations, since the branches that are not required because of zero padding can be pruned, which can decrease the complexity remarkably. In our simulations, two times oversampling is used, which indicates that the number of data subcarriers N_s is equal to $N/2$ and the remaining subcarriers are set to zero. In this configuration, for WTO-OFDM implementation the lower half of the filter bank is not used and can be pruned resulting in 50% complexity reduction. For FFT it is shown in [8] that the savings of pruning over full length FFT becomes minimal for $N_s \geq N/2$. In addition, considering the traditional butterfly implementation of FFT, only in the last stage the number of multiplications can be decreased, which corresponds to $N/2$ less multiplications. Hence, the complexity of pruned-FFT becomes

$$C_{FFT-pruned} = N \cdot \log_2(N) - N/2. \quad (3)$$

4. Simulation Results and Discussion

Simulations were carried out to evaluate a 112 Gbit/s Polmux-OFDM system. Here, only one polarization channel at a data rate of 56 Gbit/s is considered, which is generated by filling the bandwidth of 28 GHz with QPSK-modulated subcarriers. After generation, the signal is modulated onto an optical carrier with $f_0=193.1$ THz using an ideal optical IQ-modulator. The signal is transmitted over a linear optical fiber adding a certain amount of CD. At the receiver, the required OSNR for $\text{BER}=10^{-3}$ is determined by noise loading. The receiver employs an optical 10^{th} -order Gaussian filter of 30.8 GHz FWHM bandwidth. After coherent detection, the signal is demodulated in the OFDM receiver including equalization. Influences of DA- and AD-converters are not considered. The number of subcarriers was varied, which is proportional to computational complexity.

In Fig. 2, the required OSNR vs. chromatic dispersion is shown for $N_s=64$ data subcarriers for FTO-OFDM without CP and WTO-OFDM for different wavelets. Each wavelet is identified by its family name followed by the

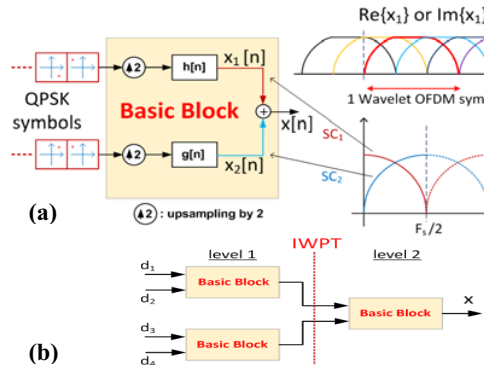


Fig. 1. (a) Basic block and (b) IWPT for 4 subcarriers. Wavelet OFDM symbols overlap both in time and frequency domain and have longer symbol duration depending on the filter length.

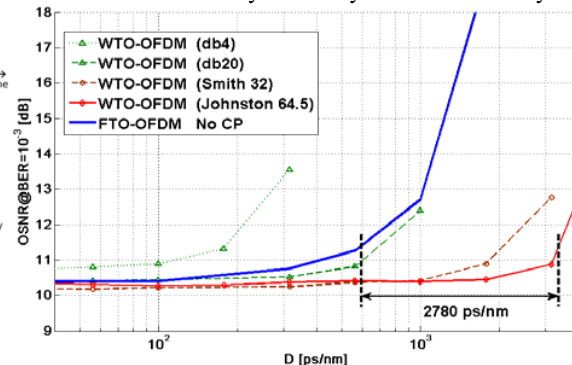


Fig. 2. WTO-OFDM can outperform FTO-OFDM (without CP) remarkably in CD-tolerance. $N_s = 64$.

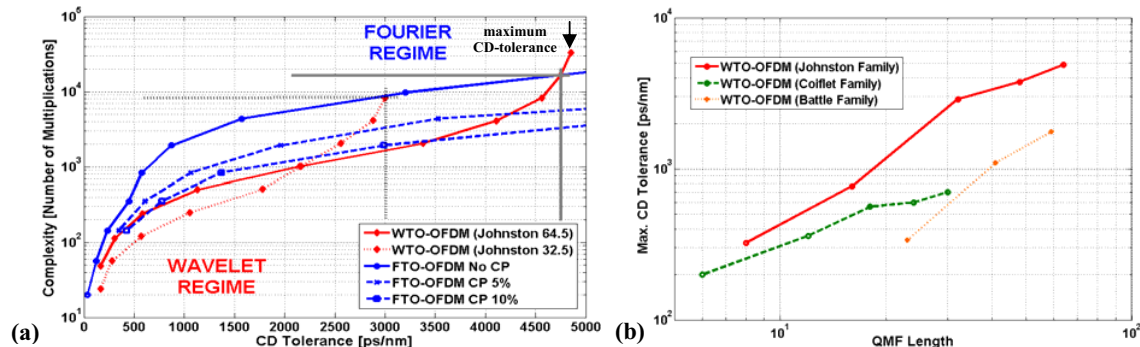


Fig. 3. (a) Wavelets show a significant reduced complexity in limited window of chromatic dispersion, (b) maximum CD-tolerance vs QMF length curves of WTO-OFDM for Coiflet, Battle [6] and Johnston wavelet families.

order of the wavelet. For the Johnston family [9], the integer and decimal parts denote the length of the associated QMF and the constraint group used in the design, respectively. For the Daubechies (db) [6] and Smith families [9] the order is equal to the length of the associated QMF. Noise tolerance of WTO-OFDM based on longer QMFs is slightly better than FTO-OFDM. CD-tolerance is measured at 1 dB OSNR penalty with respect to the minimum required OSNR value. Accordingly, CD-tolerance of WTO-OFDM based on longer QMFs outperforms FTO-OFDM. WTO-OFDM (Johnston 64.5) shows the superior performance and has a CD tolerance which is 5.6 times that of FTO-OFDM, achieving an absolute value of 3380 ps/nm in CD tolerance.

As the computational complexity of the realizations given in Fig. 2 differs, to ensure a fair comparison, the CD-tolerance comparison is also made with taking the complexities into account. The complexity versus CD-tolerance curves are presented in Fig. 3a. Since the Johnston family has superior performance compared to other considered wavelets, the comparison results are shown for the Johnston family only. A complexity reduction by a factor of 6 to 10 compared to FTO-OFDM without CP can be identified for the different wavelets in the range of moderate accumulated dispersion. In Fig. 3a, the useful application areas of FTO-OFDM without CP and WTO-OFDM are labeled by Fourier regime and wavelet regime, respectively. The border of wavelet regime can be enlarged by using Johnston 64.5 at cost of increased complexity in the low complexity range compared to Johnston 32.5. As CP addition is a method to increase the CD tolerance, the results are also compared to FTO-OFDM with 5% and 10% CP. An advantage of CP is that it does not increase the computational complexity; however, it counts for the analogue bandwidth requirements. Even for CP of 10%, the results show a comparable performance up to about 2300 ps/nm and 3400 ps/nm for the different wavelets. This suggests using the considered wavelets for dispersion compensated systems or short-haul communications to achieve remarkable complexity reductions.

The CD value above which the CD-tolerance of WTO-OFDM starts saturating is defined as the maximum CD-tolerance and is labeled for Johnston 64.5 in Fig. 3a. It can be seen from Fig. 3b that the maximum CD-tolerance within a family increases with the QMF length. In addition, for the same QMF length different wavelet families can achieve better CD-tolerance, which is the motivation to search for different wavelet families.

5. Conclusions and Outlook

WTO-OFDM was shown to give a remarkable benefit in complexity compared to FTO-OFDM for equal CD tolerance in the range of moderate accumulated dispersion. No overhead like CP is used. The achieved CD tolerances allow a reduction in either up to 10 times the complexity or 10% bandwidth for dispersion compensated systems or short-haul communications.

The wavelet diversity can be exploited further to obtain longer wavelets in the considered families where the dispersion tolerance can be expected to increase. Moreover, different wavelet families not analyzed yet in this investigation even may have significantly better performance.

References

- [1] A. J Lowery et al., "Performance of Optical OFDM in Ultralong-Haul ...", J. of Lightwave Technol., Vol. 25, No. 1, pp. 131-138, 2007.
- [2] S. L. Jansen et al., "Coherent Optical 25.8-Gb/s OFDM ...", J. of Lightwave Technol., IEEE/OSA, Vol. 26, No. 1, pp. 6-15, 2008.
- [3] S. A. Bocoï et al., "Cost Comparison of Networks Using Traditional 10 and 40 Gb/s Transponders Versus OFDM ...", OFC 2008, OThB4.
- [4] S. Sandberg et al., "Overlapped discrete multitone ...", Selected Areas in Communications, IEEE, Vol. 13, No. 9, pp. 1571-1585, 1995.
- [5] A. Jamin et al., "Wavelet packet modulation ...", Wireless Comm. & Mobile Computing, Wiley, Vol. 5, No. 2, pp. 123-137, 2005.
- [6] I. Daubechies, *Ten Lectures on Wavelets*, SIAM Publications, 1992.
- [7] S. Mallat, *A Wavelet Tour of Signal Processing*, Academic Press, 1999.
- [8] H. Sorensen et al., "Efficient computation of the DFT ...", Signal Processing, IEEE Transactions on, Vol. 41, No. 3, pp. 1184-1200, 1993.
- [9] A. Akansu et al., *Multiresolution Signal Decomposition: Transforms, Subbands, and Wavelets*, Academic Press, 2001.