Wavelet Packet based Multicarrier Modulation for Cognitive UWB Systems

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Abstract

Orthogonal frequency division multiplexing (OFDM) is a multi-carrier modulation (MCM) scheme where the sub carriers are orthogonal waves. The main advantages of OFDM are robustness against multi-path fading, frequency selective fading, narrowband interference, and efficient use of spectrum. Recently it is proved that MCM system optimization can be achieved by applying wavelet bases instead of conventional fourier bases. Wavelet packet based MCM (WPMCM) systems have overall the same capabilities as OFDM systems with some improved features. In this research the literature and analytic schemes of WPMCM system is addressed, a wavelet packet based cognitive ultra wideband (UWB) transceiver is proposed, and performance analysis of WPMCM in different wireless multipath channels is investigated. Simulation results show a significant enhancement in terms of spectral efficiency, side-lobes suppression and BER comparing to conventional OFDM.

Keywords: Orthogonal frequency division multiplexing (OFDM), wavelet packet based MCM (WPMCM), cognitive radio (CR), ultra wideband (UWB).

1. INTRODUCTION

Adaptive multi-carrier modulation (MCM) has a flexible spectrum to avoid mutual interference to other users [1]-[3]. MCM increases wireless capacity without increasing bandwidth. It divides data-stream into orthogonal parallel modulated sub-streams with lower bit rate and longer symbol time than the channel delay spread. Increasing the symbol duration leads to a robust system against ISI, channel distortion, impulse noise and fading. In wavelet packet based MCM (WPMCM) systems, the orthogonality is provided by orthogonal wavelet filters (filter banks) [4], and the real wavelet transform converts real numbers to real numbers, hence the complexity of computation is reduced. Moreover, its longer basis functions offers higher degree of side lobe suppression and decreases the effects of narrowband interference, ISI, and ICI [5]. OFDM signals only overlap in the frequency domain while the wavelet packet signals overlap in both, time and frequency. Due to time overlapping, WPMCM systems don't use cyclic prefix (CP) or any kind of guard interval (GI) that is commonly used in OFDM systems. This enhances the bandwidth efficiency comparing to conventional OFDM systems [6].

Cognitive ultra wideband (UWB) has to exploit variety of spectral opportunity, perform pulse shaping, and adapt its data rate, bandwidth, and transmit power. In a cognitive communication scenario the primary and the cognitive user are subjected to mutual interference when communicate to different receivers (Figure 1), and cognitive radio (CR) needs to avoid or cancel the interference. WPMCM is proposed as a solution for cognitive UWB challenges.

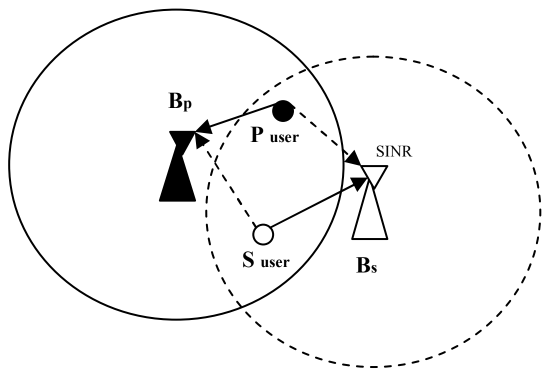


FIGURE 1: A possible arrangement of the primary and secondary receivers, base stations are indicated as Bp and Bs, respectively.

In this paper, the properties of WPMCM system and mathematical scheme are represented, power spectrum and BER are investigated by simulation results, and WPMCM is proposed for cognitive UWB systems. The remainder sections are organized as follows. Section 2 is related works on wavelet based MCM systems. Wavelet packet based MCM properties are described in section 3. System description and analytical relations are provided in section 4. In section 5, cognitive UWB transceiver design is proposed, and simulation results and discussion are described in section 6. We summarize the research in section 7.

2. RELATED WORKS

There is a considerable literature addressing the use of WPMCM and its performance evaluation comparing with conventional method. A closed form formula in [7] is derived to define convolution's counterpart in the wavelet domain, and a wavelet based multicarrier modulation framework presented by discrete wavelet transform (DWT) Mallat's algorithm. Performance analysis of IEEE 802.15.3a channel models for multiband UWB proved that the overhead and the transceiver structure for the WB-MUWB are less complex than those for the FB-MUWB; therefore DWT could be considered as an attractive technique in future multicarrier UWB systems.

In [8] authors studied symbol error rate (SER) of both conventional OFDM and Gabor basis WPMCM in AWGN channel for fast intercity trains, and showed that this new technique with a moderate complexity avoids the spectral efficiency loss. Testing this technique in more realistic channels is an idea to continue their research. For radar applications, Mohseni et.al in [9] replaced the conventional OFDM multicarrier modulation with the WPMCM in order to get a more flexible signal design approach. These designed radar signals have very low side lobe levels in their ambiguity functions and high spectral efficiency. The requirements imposed in the design of usable wavelets and wavelet packets for multicarrier modulation are studied in [10]. According to this article, for perfect reconstruction of data the wavelets have to satisfy bi-orthogonal property. Another real time application of the system is reported in [11] where WPMCM for V-BLAST [12] (vertical Bell laboratories layered space time) is discussed. According to [11] the bit error rate

(BER) performance of the wavelet based V-BLAST system is superior to their Fourier based counterparts.

The major drawback of MCM systems is the peak-to-average power ratio (PAPR) problem. High peaks of the transmitted signal drive the power amplifiers operating near nonlinear saturation regions which degrade the power efficiency and system performance. Hence, it is necessary to transmit signals with lower PAPR because of operating range of power amplifiers. In [13] authors reported reducing in PAPR by a Haar WPMCM system with Hadamard spreading codes. WPMCM system is also sensitive to time synchronization errors resulting from its overlapping symbols in the time domain. OFDM can easily exploit CP to reduce the effects of timing error or dispersive channel. Furthermore, the ISI in OFDM is generated by overlapping of two successive symbols, while in the case of WPMCM, ISI is generated by overlapping of a number of consecutive symbols. Hence, WPMCM is very sensitive to even small timing differences between transmitter and receiver. In [14] the performance of wavelet packet modulation (WPM) systems using several well known wavelets in the presence of timing offset is compared with OFDM. As a future work authors proposed to design wavelet and scaling filters that would minimize the interference energy from timing error. They also suggested using complex wavelets to reduce WPM time shift sensitivity, and designing a robust synchronization scheme to tackle large timing offsets.

Channel estimation is another challenge to be tackled by researchers. In traditional OFDM system, channel estimation is performed by pilot symbol assisted modulation (PSAM) with pilot interpolation in time domain or frequency domain. More pilots, lower bandwidth efficiency and higher system complexity. The channel estimation issue for WPM system has been addressed in [15] and a novel pilot arrangement is designed based on wavelet packet theory for WPM system to achieve higher speed transmission with lower bit error rates. In [5] channel estimation for WPM is surveyed and indicated that ANNs (Artificial Neural Networks) method is more proper than LMMSE estimation. As their future work, authors proposed development of wavelet theory and post- equalization to cancel the interference caused by overlapping symbols.

3. WAVELET PACKET BASED MCM FEATURES

The wavelet basis functions are localized in time (or space) and frequency, and have different resolutions in these domains. Wavelet transforms are broadly classified as continuous and discrete wavelet transforms. The continuous wavelet transform (CWT) of a continuous signal $x(t)$ is defined as the sum of all time of the signal multiplied by scaled, shifted versions of the wavelet waveforms. Discrete wavelet transform (DWT) analyzes the signal at different frequency bands with different resolutions by decomposing the signal into an approximation containing coarse and detailed information. DWT employs two sets of functions, known as scaling and wavelet functions, which are associated with low pass and high pass filters. The decomposition of the signal into different frequency bands is simply obtained by successive high pass and low pass filtering of the time domain signal. Wavelet packet transform (WPT) decomposes the high frequency bands which are kept intact in the DWT; hence it obtains richer resolution. Some advantages of wavelet transform are described as follows.

3.1. Multi-rate Property

The main property of the WPT is the semi-arbitrary division of the signal space. WPT still leads to a set of orthogonal functions, even if the construction iterations are not repeated for all sub-branches. From a multicarrier communication system perspective, this maps into having subcarriers of different bandwidths and symbol length to create a multi-rate system and enhance the quality of service (QoS) of wireless systems.

3.2. Configurable Transform Size

The iterative nature of the wavelet transform allows for a configurable transform size and hence a configurable number of carriers. This facility can be used, for instance, to reconfigure a transceiver according to a given communication protocol; the transform size could be selected according to the channel impulse response characteristics, computational complexity or link quality.

3.3. Noise and Interference Suppression

By flexible time-frequency resolution, the effect of noise and interference on the signal can be minimized. Wavelet based systems are capable of avoiding known channel disturbances at the transmitter, rather than waiting to cancel them at the receiver. In [16] a WPMCM transmission system, for multi-rate integrated service is demonstrated. The performance of this system under impulse noise and single tone interference is reported to be superior to existing Fourier based variants. WPT digital modulated signals are mapped into their own Time-Frequency Atoms (t-f atoms) which will be utilized in multiplexing of transport orthogonally. Tone interference and impulse noise cause distributed effects in the WPM system.

3.4. Robustness against ISI and ICI

The performance of MCM system depends on the set of waveforms that the carriers use. The wavelet scheme reduces the sensitivity of the system to harmful channel effects like Inter-symbol interference (ISI) and Inter-carrier interference (ICI). Authors in [18] replaced the fourier-based complex exponential carriers of a multicarrier system with orthonormal wavelets. The wavelets are derived from a multistage tree-structured Haar and Daubechies orthonormal quadrature mirror filter (QMF) bank. The authors in [17] compared both OFDM and WPMCM in the context of PLCs and proved that WPMCM has higher transmission efficiency, deeper notches, robustness to narrowband interference (NBI) or impulsive noise, and lower circuit cost as fewer carriers than in conventional or windowed OFDM can be used. An improved performance with respect to reduction of the power of ISI and ICI is reported in Table 1 that makes comparison between orthonormal Haar wavelets and conventional OFDM. This work is extended in [19] with empirical investigations on a model obtained from the measurements of a practical high speed and low-voltage power line communication channel (PLC), the research exhibits superiority of WPMCM to traditional OFDM especially regarding to ISI and ICI mitigation.

Conventional OFDM	ISI_{av}[dB]	-1.07	-0.72	-0.54
	ICI_{av}[dB]	-6.60	-8.16	-9.31
Haar-WPMCM	ISI_{av}[dB]	-2.41	-1.62	-1.23
	ICI_{av}[dB]	-7.49	-12.94	-18.67
Channel excess delay		T	T	T
Number of carriers		8	12	16

TABLE 1: Averaged normalized power of interference for MCM systems.

4. SYSTEM DESCRIPTION

At the transmitter the data stream $X = (x[1], x[2], \dots, x[n], \dots, x[N])$, is first converted from serial to parallel sequences S_k and then modulated with *M*-array inverse wavelet packet transform (IWPT). Figures 2a and 2b, show the wavelet packet based MCM transceiver operating Mallat's fast algorithm [20].

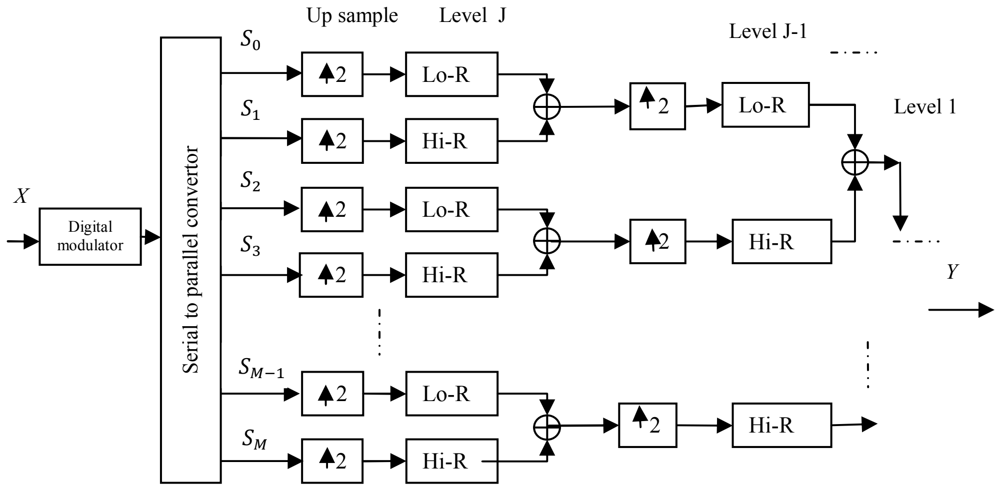


FIGURE 2a: Wavelet packet based MCM transmitter part, including reconstruction filters.

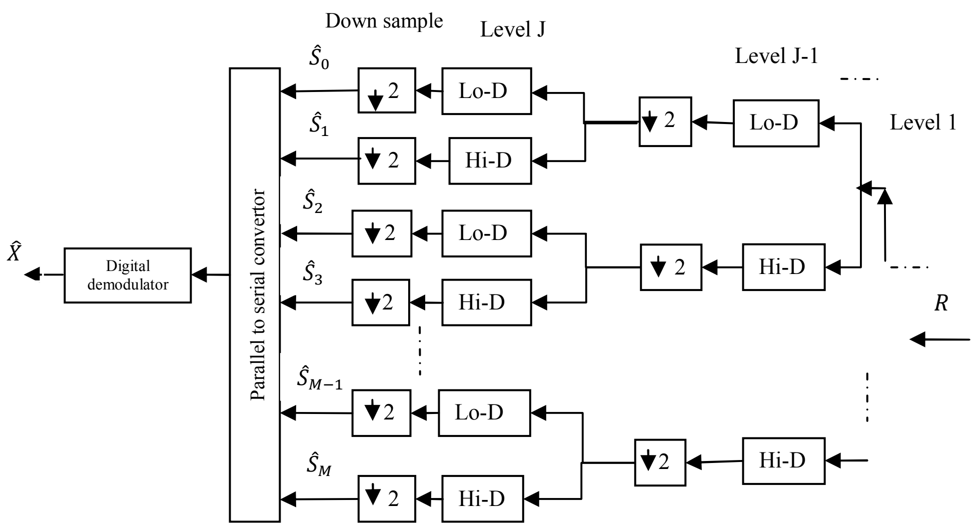


FIGURE 2b: Wavelet packet based MCM receiver part, including decomposition filters.

The transmitted signal *Y,* is composed of successive K symbols, as the sum of *M* amplitude modulated waveforms by ϕ_k. It can be expressed using matrix notations as:

$$Y = \sum_k S_k . \phi_k \tag{1}$$

where $Y = (y[1], y[2], \dots, y[n], \dots, y[N])$, is transmitted signal, $S_k = (s_0[k], s_1[k], \dots, s_m[k], \dots , s_{M-1}[k])$, is constellation encoded k-th data symbol, and

$$\phi_k = \begin{pmatrix} \varphi_0[1-kM] & \cdots & \varphi_0[N-kM] \\ \vdots & \varphi_m[n-kM] & \vdots \\ \varphi_{M-1}[1-kM] & \cdots & \varphi_{M-1}[N-kM] \end{pmatrix} \tag{2}$$

is the waveforms matrix which $\varphi_m[n]$ are mutually orthogonal to reduce the symbol errors, i.e.

$$\varphi_i[n] * \varphi_j[n] = \delta[i-j], \tag{3}$$

where $*$ indicates a convolution operation and δ represents the Dirac function.
The relationship between the number of iterations *J* and the number of carrier waveforms *M* is given by $M = 2^J$.

In the wavelet packet scheme, we limit our analysis to subcarrier waveforms defined through a set of FIR filters, and implemented by Mallat's fast algorithm [21] with less complexity for wireless communication. In orthogonal wavelet systems, quadrature mirror filter pair (QMF) consists of the scaling filter h_{lo}^{rec} and dilatation filter h_{hi}^{rec}, and knowledge of the scaling filter and wavelet tree depth is sufficient to design the wavelet transform. The scaling filter h_{lo}^{rec} and dilatation filter h_{hi}^{rec}, and the corresponding reversed filters h_{lo}^{dec} and h_{hi}^{dec}, are used to form a wavelet packet tree. These filters satisfy following conditions:

$$\sum_{n=-\infty}^{n=\infty} h_{lo}^{rec}[n] = 2, \tag{4}$$

$$\sum_{n=-\infty}^{n=\infty} h_{lo}^{rec}[n] h_{lo}^{rec}[n-2q] = 2\delta(q), \tag{5}$$

$$h_{hi}^{rec}[n] = (-1)^n\, h_{lo}^{rec}[\lambda - n - 1], \tag{6}$$

where λ is the span of the filters.
The carrier waveforms are obtained by iteratively filtering the signal into high and low frequency components. The waveforms $\varphi_m[n]$ are derived by *J* successive iterations as the following recursive equations:

$$\begin{cases} \varphi_{j,2m}[n] = h_{lo}^{rec}[n] * \varphi_{j-1,m}[\frac{n}{2}] \\ \varphi_{j,2m+1}[n] = h_{hi}^{rec}[n] * \varphi_{j-1,m}[\frac{n}{2}] \\ \varphi_{0,m}[n] = \begin{cases} 1, n = 1 \\ 0, else \end{cases} \end{cases} \tag{7}$$

where *j* is the iteration index, $1 \le j \le J$, and *m* the waveform index $0 \le m \le M-1$. Using usual notation in discrete signal processing $\varphi_{j,m}[\frac{n}{2}]$ denotes two version up-sampling of $\varphi_{j,m}[n]$.
The type of WPT algorithm depends on the choice of mother wavelet, the number of levels of expansion, and signal specifications such as periodic, non-periodic, extended and finite WPT. Time and frequency domain localizations are not independent and a waveform with higher frequency domain localization can be obtained with longer time support. Furthermore, short duration waveforms have shorter symbol duration than the channel coherence time, limit the modulation-demodulation delay, and require less memory and less computation.

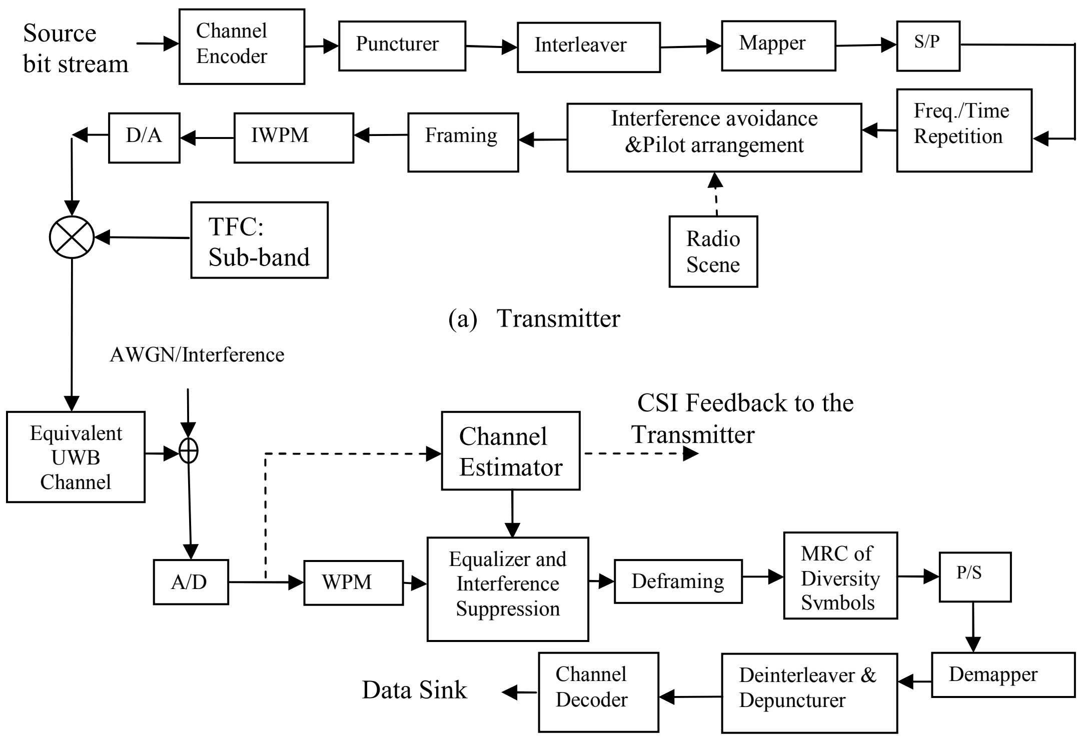
For the evaluation of a wireless channel, we assume a channel *H*, with *L* multi-paths, $H = (h[0], h[1], \dots, h[l], \dots, h[L-1])$ and received signal at the output of the channel can be written as:

$$R = H.Y + V\ , \tag{8}$$

where $R = (r[1], r[2], \dots, r[n], \dots, r[N])$, is the received signal, and $V = (v[1], v[2], \dots, v[n], \dots, v[N])$, is additive white Gaussian noise (AWGN).

5. TRANSCEIVER DESIGN

Our proposed WPMCM System framework including channel state information (CSI) feedback is illustrated in figures 3**.** The information bits are firstly grouped and mapped into MPSK or M-QAM. Then the serial data stream is transformed to N parallel lines, where N is the number of subcarriers which is dependent on channel state. So pilots can be inserted into the N lines of signals with particular pilot arrangement strategy, then obtained N lines of signals can be modulated through inverse wavelet packet modulation (IWPM). In the receiver time and frequency diversity are exploited in the system, the maximal ratio combining (MRC) technique is used to combine different diversity branches.



(a) Transmitter

(b) Receiver

FIGURE 3: Cognitive multiband UWB transceiver via WPMCM.

A multiband UWB system is provided with symbols of duration T, bandwidth 528 MHZ, and 128 samples to be transmitted in different sub-bands. For the wavelet based system cyclic prefix is replaced by data bits. Multiple-access can be introduced in the form of time-frequency hopping codes similar to multiband OFDM. Wavelet packet basis and filter pairs are selected due to the type of system application. In the case of MCM, wavelet packet bases are time limited and smooth, well confined in frequency, and orthogonal or linearly independent.

6. RESULTS AND DISCUSSION

In simulation part, we consider 128 wavelet packet equally spaced carriers to be adaptively deactivated for transmission spectrum shaping according to the primary users band (Figure 4).

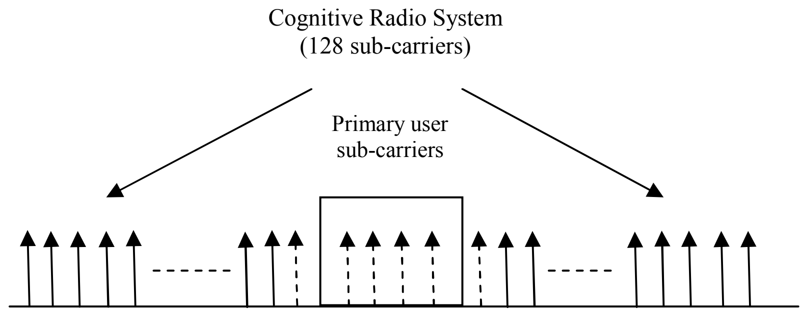


FIGURE 4: CR coexistence with primary user Characteristics, solid lines show active subcarriers and dot lines indicate deactivated subcarriers in the band of or adjacent to primary user.

We assume a WPMCM system which is presented in Figure 5. The information bits are firstly modulated by 16-QAM constellation mapping. Then the serial data stream is transformed to 128 parallel subcarrier lines, pilot symbols are inserted and signals are modulated through IWPT. For the wavelet packet based system, cyclic prefix is replaced by data bits. At the receiver side, the zero forcing equalizer is provided to compensate the effects of channel distortion and WPT block is applied for demodulation of data.

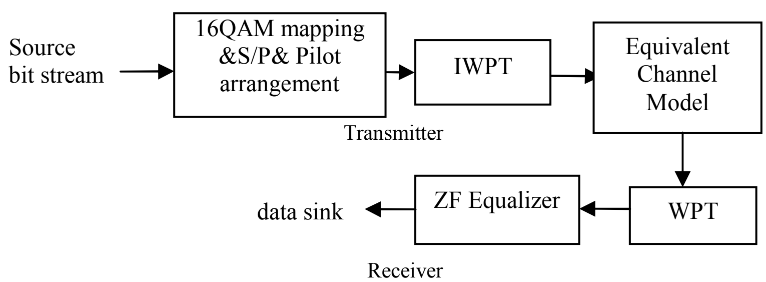
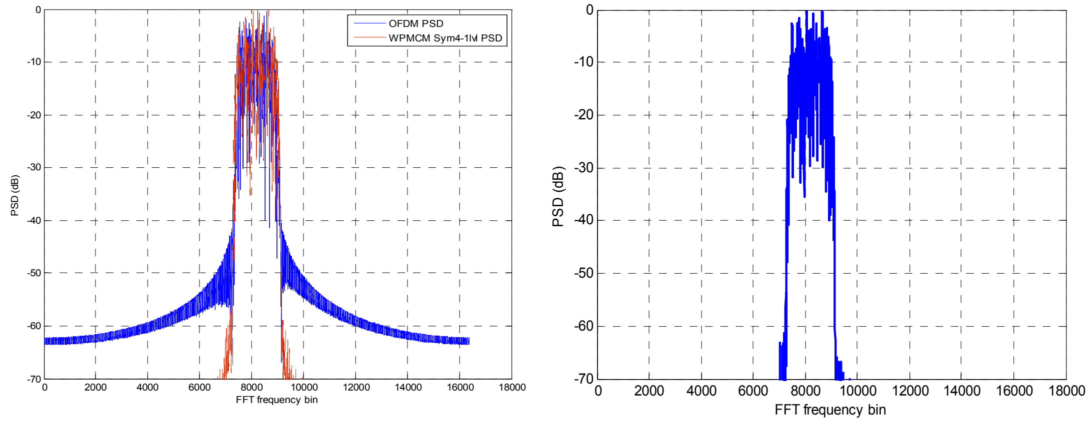


FIGURE 5: WPMCM transceiver for simulation.

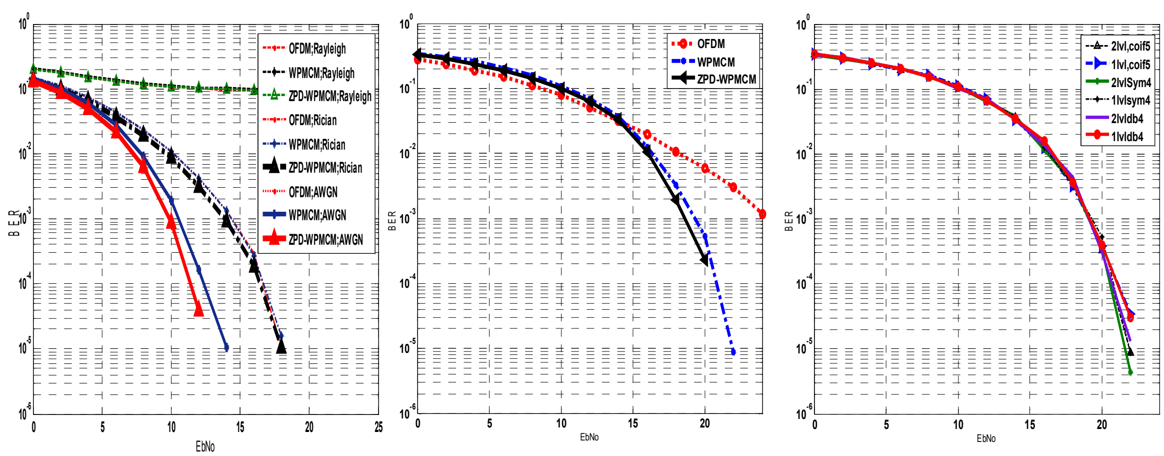
In conventional OFDM large side-lobes result in out-of-band (OOB) radiations, thus, coexistence of primary and secondary users depends on side-lobes suppression. Figures 6(a) compares power spectrum density (PSD) of conventional OFDM and WPMCM. According to the graphs, WPMCM enhances the side-lobes suppression effectively accompanied by high spectral efficiency caused by removing the cyclic prefix. These figures illustrate that the occupied bandwidth of WPMCM is far less than OFDM. PSD of zero-padded WPMCM shown in figure 6(b) has minor side-lobes improvement comparing to WPMCM.

Simulation results of Figures 7(a, b and c) compare the bit error rate (BER) of conventional OFDM and WPMCM signal with 1 level wavelet packet tree with Sym4 family, versus the Signal-to-Noise Ratio (SNR) in the presence of different channel conditions. According to the Figure 7(a), WPMCM signal has almost the same BER as conventional OFDM, but for zero-padded WPMCM the BER is lower and performance is improved for all channel conditions with the cost of spectral efficiency. For zero padded WPMCM in AWGN channel, improvement at BER of 10^{-4} is 1dB with respect to conventional OFDM. In the two next cases, (Figures 7b,7c), we consider a two taps channel with additional AWGN effect and zero forcing equalizer in the receiver. Figure 7(b) shows that both WPMCM and zero-padded WPMCM have better BER comparing to OFDM for SNR higher than 15 dB. The performance improvement at $10^{-3}$is 6 dB and 7 dB for WPMCM and zero padded WPMCM respectively. In figure 7(c), BER performance doesn’t change significantly with various choices of wavelet filter families, but at high SNR situation, two level wavelet packet trees represent superior performances to one level wavelet packet trees.



(a) (b)

FIGURE 6: Power spectral density (obtained by FFT length of 16384) of (a) conventional OFDM and 1 level WPMCM-Sym4, (b) zero padded 1 level WPMCM-Sym4.



(a) (b) (c)

FIGURE 7: BER comparison between conventional OFDM and WPMCM-Sym4 for (a) AWGN, Rayleigh and Rician channel conditions, (b) in the presence of a two taps channel distortion and AWGN,(c) different Wavelet families and tree levels.

7. CONCLUSION

In this research wavelet packet based multicarrier modulation is recommended for cognitive multiband UWB systems as an efficient solution to meet adaptive and cognitive goals. Literature is surveyed, and analytical approach of WPMCM transceiver is addressed. Power spectrum density graphs shows that WPMCM has high spectral efficiency accompanied by significant side-lobes suppression. Finally we investigated the BER performance and power spectral density of WPMCM under different channel models and wavelet families. BER improvement is achieved by WPMCM comparing to the conventional OFDM. As future work, we compare the conventional OFDM and wavelet based MCM-UWB systems under standard IEEE 802.15.3a channel models (CM1-CM4) for wireless personal area networks (WPAN). Study on narrowband interference mitigation of WPMCM UWB systems is the next open contribution.

8. REFERENCES

1. T.A. Weiss, F.K. Jondral. "*Spectrum Pooling: An Innovative Strategy for the Enhancement of Spectrum Efficiency*", IEEE Communications Magazine, 42:8-14, 2004.
2. M.K. Lakshmanan, I. Budiarjo and H. Nikookar. "*Maximally Frequency Selective Wavelet Packets Based Multi-Carrier Modulation Scheme for Cognitive Radio Systems*", The 50th IEEE Global Communications Conf.(Globecom), Washingthon DC, USA, 2007.
3. M.K. Lakshmanan, H. Nikookar. "*Optimum Wavelet Packet Construction for Multicarrier-based Cognitive Radio System*", The 10th Int. Symp. on Wireless Personal Multimedia Communications, Jaipur, India, 2007.
4. G. Strang, T. Nyugen. "*Wavelets and Filter Banks*", Wellesley/Cambridge Press, 1996.
5. X.Wu, F. Tian, J. Liu. "*Efficient Spectrum Multiplexing Using Wavelet Packet Modulation and Channel Estimation Based on ANNs*", Int. Conf. on Audio, Language and Image Processing, Shanghai, China, 604-608, 2008.
6. M.K. Laksmanan, H. Nikookar. "*Review of wavelets for digital wireless communication*", Wireless Pers. Commun. 37:387-420, 2006.
7. R. Dilmaghani, M. Ghavami. "*Comparison between wavelet-based and Fourier-based multicarrier UWB systems*", IET Commun., 2(2):353-358, 2008.
8. T. Boukour, M. Chennaoui, A. Rivenq, J.M. Rouvaen, M. Berbineau. "*A New WOFDM Design for High Data Rates in the case of Trains Communications*",IEEE Int. Symp. on Signal Processing and Information Technology(ISSPIT), Athenes, Greece, 2005.
9. R. Mohseni, A. Sheikhi, M. A. Masnadi Shirazi. "*UWB Radars Based on Wavelet Packet OFDM Signals*", IEEE Int. Conf. on Ultra-Wideband, Hannover, 2:89-92, 2008.
10. C.V. Bouwel, et.al. "*Wavelet Packet Based Multicarrier Modulation*", IEEE Benelux Symposium on Communications and Vehicular Technology, Leuven, Belgium, 2000.
11. Z. Rafique, N. Gohar, M.J. Mughal. "*Performance Comparison of OFDM and WOFDM Based V-BLAST Wireless Systems*", IEICE Transactions on Communications, E88-B (5):2207-2209, 2005.
12. P.W. Wolniansky, et.al. "*V-BLAST: An Architecture for Realizing Very High Data Rates Over the Rich-Scattering Wireless Channel*", ISSSE-98, Pisa, Italy, 1998.
13. K. Anwar, et.al. "*PAPR Reduction of OFDM Signals Using Iterative Processing and Carrier Interferometry Codes*", IEEE Int. Symp. on Intelligent Signal Processing and Communications System (ISPACS), Seoul, Korea, 48-51, 2004.
14. H. Nikookar, M.K. Lakshmanan. "*Comparison of sensitivity of OFDM and Wavelet Packet Modulation to time synchronization error*", The 19th Int. Symp. on Personal, Indoor and Mobile Radio Communications(PIMRC2), Athens, greece,1-6, 2008.
15. M. Yang, Z. Liu , J.Dai. "*Frequency Selective Pilot Arrangement for Orthogonal Wavelet Packet Modulation Systems*", Int. Conf. on Computer Science and Information Technology(ICCSIT), Singapore, 2008.
16. W. Yang, et.al. "*A Multirate Wireless Transmission System Using Wavelet Packet Modulation*", IEEE 47th Vehicular Technology Conf., Phoenix, AZ, USA, 1: 368-372, 1997.
17. S. Galli, H. Koga, N. Kodama. "*Advanced Signal Processing for PLCs: Wavelet-OFDM*", IEEE Int. Symp. on Power Line Communications and Its Applications, 187-192, 2008.
18. B.G. Negash, H. Nikookar. "*Wavelet-Based Multicarrier Transmission Over Multipath Wireless Channels*", IEE Electronics Letters, 36(21):1787-1788, 2000.
19. Y. Zhang, S. Cheng. "*A Novel Multicarrier Signal Transmission System Over Multipath Channel of Low-Voltage Power Line*", IEEE Transactions on Power Delivery,19(4):1668-1672, 2004.
20. A. Jamin, P. Mahonen. "*Wavelet packet Modulation for Wireless Communications*", Wireless Communications & Mobile Computing Journal, John Wiley and Sons Ltd., 5(2):123-137, 2005.
21. S. Mallat. "*A wavelet tour of signal processing*", 2nd ed. Academic Press, 1999.