Performance Comparison of Wavelet Packet Transform (WPT) and FFT-OFDM System Based on QAM Modulation Parameters in Fading Channels

Haitham J. Taha, Student Member, IEEE and M. F. M. Salleh, Member, IEEE
School of Electrical and Electronic Engineering
Universiti Sains Malaysia
Seri Ampangan, 14300 Nibong Tebal, Pulau Pinang, Malaysia
Email: haithm1969@yahoo.com; fadzlisalleh@eng.usm.my

Abstract: - Orthogonal Frequency Division Multiplexing (OFDM) has been widely adopted in many applications due to its good spectral performance and low sensitivity to impulse noise and multipath channels. It has been widely adopted and standardized in many applications today. It is well known in OFDM that a cyclic prefix (CP) is appended to each symbol in order to mitigate the effect of Inter-Symbol-Interference (ISI). However, this reduces the spectral efficiency. A perfect reconstruction using wavelet packet transmultiplexer in OFDM transceiver counters the degrading effect of ISI, and also conserves bandwidth. In comparison to FFT-OFDM, Wavelet Packet Modulation (WPM) offers much lower side lobes in the transmitted signal, which reduces inter carrier interference (ICI) and narrowband interference (NBI). WPM improves spectral efficiency due to the exclusion of CP. Nevertheless, it requires an efficient equalization technique to counter the ISI and ICI. Wavelet based OFDM has been suggested to improve BER performance of transceiver in wireless communication. In this paper, a study of wavelet packet transform modulation WPT-OFDM scheme is conducted, and the performance comparison is made against the traditional FFT-OFDM over various fading channels. The analysis is done using various number of modulation QAM constellation points. Specifically, the analysis is on the effect of QAM constellation points in AWGN channel, flat fading channel and frequency selective fading channels. Simulation results using QAM Modulation points (8 to 64 Point), and the BER best performance of WPT- OFDM system is when the QAM Modulation parameter (QAM = 8) in all channels.

Keywords: FFT-OFDM, Wavelet Packet, WPT-OFDM.

1. Introduction

Multi carrier modulation (MCM) is very efficient transmission technique for wireless communication system. The modulation technique works by simultaneously transmitting N data symbols through N carriers, thus reducing the symbol rate to one N^{th} of the original symbol rate. Also it increases the symbol duration by N times. The technique offers more robust against intersymbol interference (ISI) caused by channel dispersions and multipath interference. In additions, the MC system divides the original frequency band into several narrow bands, thus making the system less sensitivity to wide-band impulse noise and fast channel fades as compared to the single carrier modulation technique.

Orthogonal Frequency Division Multiplexing (OFDM) employs MCM technique, and received considerable attention due to the need for high speed data transmission. Orthogonal subcarriers allow their spectrums to overlap which achieves the high spectral efficiency. As long as the subcarriers preserve their orthogonality, adjacent subcarriers do not interfere with each other. Nowadays, OFDM has been accepted as the standard in several wired line and wireless applications such as the European Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB) and WiMAX (IEEE 802.16) [1].

The Wavelet based OFDM or in particular the Wavelet Packet Modulation (WPM) is an alternate approach to the conventional OFDM scheme that exploits the self and mutual orthogonality properties of wavelet packet basis functions. Unlike the traditional FFT-OFDM which divides the whole bandwidth into several orthogonal and overlapping subbands of equal bandwidths, WPM uses discrete wavelet packets transform to multiplex the transmission. In this technique, the data are assigned to the wavelet subbands of having different time and frequency resolutions. Thus, this makes the WPM based OFDM very flexible.

Furthermore, it has been shown in [2] that using WPM is more robust to narrowband interference and multipath propagation loss than FFT-OFDM. In that work, it has also shown that the signals are more spectrally efficient than the conventional FFT-OFDM signals.

There are some significant differences between these two systems. FFT-OFDM signals only overlap in the frequency domain, while the WPM-OFDM signals overlap in both, time and frequency domains. Due to time overlap in WPM-OFDM system, this allows the system to exclude the use of CP codes or any kind of guard interval (GI) that is commonly used in FFT-OFDM system. In FFT-OFDM the CP codes are used to overcome ISI caused by dispersive channel.

There have been many works done in wavelet based OFDM systems. The work in [3] presents the performance comparisons of DFT-OFDM and DWT-OFDM on three different channel models using BPSK modulation scheme. While [2] presents the performance comparison of conventional DFT with Discrete Wavelet Packet Transform (DWPT) in an OFDM transceiver. The performance comparison of DFT-OFDM and wavelet packet based OFDM (WOFDM) using arbitrary FIR channel with different types of wavelet packets is presented in [4]. The work in [5] investigates the bit error rate (BER) performances of OFDM and WPM systems in the presence of carrier frequency offset and phase noise.

In [6] performance comparison of OFDM and WPM for several multipath wireless channels is presented. They propose a novel application of zero-forcing (ZF) and minimum mean square error (MMSE) algorithms as time-domain channel equalization techniques for WPM systems. In [7] the BER performance of conventional DFT - OFDM system is compared with discrete wavelet transform (DWT)-OFDM system and discrete cosine transform (DCT)-OFDM system in an AWGN environment.

Meanwhile, the use of Quadrature Amplitude Modulation (QAM) modulation in OFDM system scheme has become very popular since it offers wider range of envelope fluctuation as explains in [8]. Besides, it provides higher spectral efficiency due to the usage of amplitude and phase modulation which effectively increase the channel capacity [9].

This paper investigates the impact of the number of QAM constellation points over FFT-OFDM and WPT-OFDM in AWGN channel, Flat Fading channel and Selective Fading channel. The analysis is done for various numbers of modulations QAM constellation points (8 to 64), and simulated over these channels. Simulation results show that the best BER performance exhibits by the WPT-OFDM system, when the number of modulation QAM is 8 for all channels.

The rest the paper is organized as follows; section 2 presents the FFT-OFDM system model, section 3 presents the Discrete Wavelet Packets Transform (DWPT), section 4 presents the DWPT-OFDM system model. Section 5 presents the channel estimation for OFDM systems and section 6, and 7 presents the simulation results and conclusions respectively.

2. FFT-OFDM System Model

The simulation model of FFT-OFDM is shown in Figure 1 which is obtained from [10, 11]. The input data stream is first mapped into the QAM modulation scheme according to the QAM constellation mapping. Then the complex number output is converted from serial to parallel into N-points IFFT to generate the OFDM symbols.

The output data from IFFT is now converted from parallel to serial and a cyclic prefix is added to the data. The data are sent via wireless channel after being converted to frame structure (serial data stream). The frame structure consists of the modulated data and the pilot signal which is used for channel estimation and compensation. The channel consists of a multipath fading (flat fading channel or frequency selective fading channel) with AWGN.

At the receiver the reverse operations of the encoding processes are employed. The cyclic prefix is removed and a serial to parallel conversion is done for the signal. A FFT with N points is used to convert the signal from time to frequency domain. Then the effective channel is compensated after the OFDM demodulation, the signal demapper is used to recover the transmitted signal.

3.Discrete Wavelet Packets Transform (DWPT)

Wavelet packets transform has been first introduced for data compression due to it functions are localized in both time and frequency domains. The construction of a wavelet packets basis starts from a pair of quadrature mirror filters (QMF), g1 and g_0, satisfying the following conditions [12, 13];

$$\sum_{n=-\infty}^{\infty} g_1(n) = 2 \tag{1}$$

$$\sum_{n=-\infty}^{\infty} g_1(n)\, g_1(n-2k) = 2\delta(k) \tag{2}$$

$$g_0(n) = (-1)^n\, g_1(L-n-1) \tag{3}$$

The sequence of functions $\varphi_n(x)$, called wavelet packets, are *recursively* defined by the QMF $g_1(n)$ and $g_0(n)$ as [12, 13];

$$\varphi_{2n}(x) = \sum_{k\in z} g_1(k)\varphi_n(2x-k) \tag{4}$$

$$\varphi_{2n+1}(x) = \sum_{k\in z} g_0(k)\varphi_n(2x-k) \tag{5}$$

The first two functions of this sequence $\varphi_0(x)$ and $\varphi_1(x)$ are exactly the scaling function and its corresponding wavelet function from a multiresolution analysis. Since the two functions $\varphi_{2n}(x)$ and $\varphi_{2n+1}(x)$ are generated from the same function $\varphi_n(x)$, they are called the "children" functions of the "parent" $\varphi_n(x)$. The two operators, also known as filtering-down sampling processes using the QMF $g_1(n)$ and $g_0(n)$, are defined as [12, 13]:

$$G_1\{x\}(2n) = \sum_{k\in z} x(k) g_1(k-2n) \tag{6}$$

$$G_0\{x\}(2n) = \sum_{k\in z} x(k) g_0(k-2n) \tag{7}$$

These two operators are used to decompose (analyze) any discrete function $x(n)$ on the space $l^2(Z)$ into two orthogonal subspaces $l^2(2Z)$. In each step two coefficient vectors has a length half of the input vector are produced. Thus, the total data length remains unchanged. The process continues and stops at any desired step. The output coefficient vectors become scalars for the deepest decomposition level. This decomposition process is named as Discrete Wavelet Packet Transform (DWPT). The transformed coefficient vectors are orthogonal and the original signal $x(n)$ can be recovered from the coefficient vectors by the inverse transform. This process is defined as a series of up-sampling-filtering using the reversed filters g_1 (-n) and g_0 (-n). The wavelet packets function set defined in Eq. (4) and Eq. (5) can also be constructed using the Inverse DWPT (IDWPT) with the dual operators of Eq. (6) and (7) are defined as [12, 13];

$$G_1^{-1}\{x\}(2n) = \sum_{k\in z} x(k) g_1(n-2k) \tag{8}$$

$$G_0^{-1}\{x\}(2n) = \sum_{k\in z} x(k) g_0(n-2k) \tag{9}$$

The process of constructing a wavelet packet function set can be more clearly seen via the wavelet packet construction tree shown in Figure 2. Each wavelet packet function is constructed starting from a leaf of this binary tree with an impulse δ(n) going up node by node until reaching the root of the tree. The operator from one node to an upper layer node is one of the above operators G_1^{-1} and G_0^{-1} depending on the left/right direction.

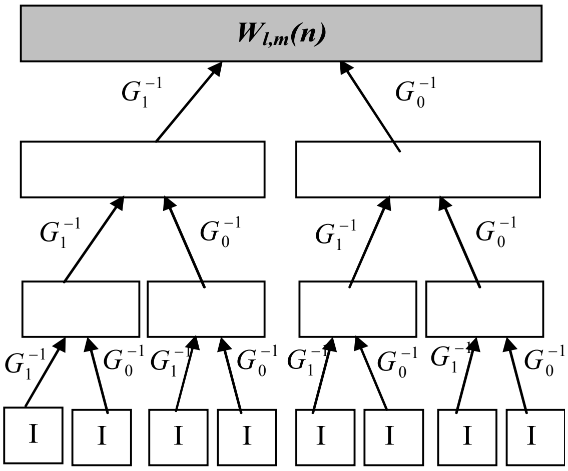

Figure 2: Wavelet packet construction tree [12].

4. DWPT-OFDM System Model

Figure 3 shows the transmitter part of DWPT-OFDM. The data symbols are converted from serial to parallel of block data for N OFDM subcarriers. Thus, decreases the symbol rate by a factor of N that is equal to the number of sub-carriers.

These symbols are modulated to different subcarriers through an IDWPT block. This modulation/mapping is equivalent to the Inverse Discrete Fourier Transform block in the conventional sinusoid waveform based multicarrier system. The inverse wavelet packet construction tree for two levels is shown in Figure 4.

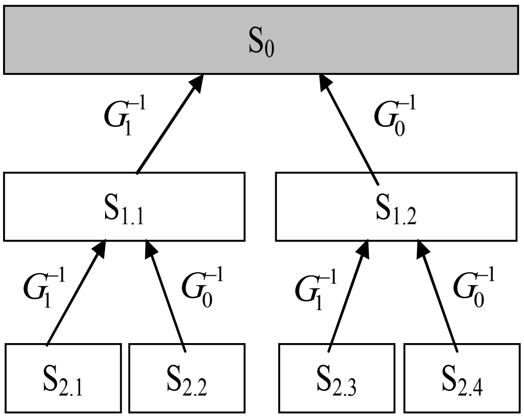

Figure 4: Inverse wavelet packet construction tree for two levels [12].

5. Channel Estimation

At the receiver, the transmitted signals are received from the multipath fading channel. After removing the guard interval, performing DFT and channel estimation, the demodulated signal of the k th sub-carrier can be represented as [14] [15]:

$$Y(k) = X(k)H(k) + W(k) \quad 0 \le k \le N-1 \tag{10}$$

Where N is the number of sub-carriers, $H(k)$ and $W(k)$ represent the frequency transfer function of the channel and additive white Gaussian noise (AWGN) with zero mean and variance of σ_w^2 . Then the binary information data is obtained back in "signal demapper" block as shown in Figure 3 given as [14] [15].

$$X_e(k) = \frac{Y(k)}{H_e(k)} \quad k = 0,1,.....,N-1 \tag{11}$$

5.1 LS and MMSE Estimators

In this section we study the performance of the some channel estimation methods. We consider the popular least squares (LS) and minimum mean-square-error (MMSE) techniques which require less knowledge of the channel statistics.
For convenience, Eq. (10) can be written in matrix notation given as [16];

$$Y = XFh + W \tag{12}$$

Where

$$X = diag(X_0, X_1, \ldots, X_{N-1}) \tag{13}$$

Let F be the DFT-matrix given as [16];

$$F = \begin{bmatrix} W_N^{00} & \cdots & W_N^{(N-1)0} \\ \cdots & \cdots & \cdots \\ W_N^{0(N-1)} & \cdots & W_N^{(N-1)(N-1)} \end{bmatrix} \tag{14}$$

If the time domain channel vector h is Gaussian and uncorrelated with the channel noise, the frequency domain MMSE (Minimum Mean Square Estimation) estimation for h is given by [16]:

$$\hat{H}_{MMSE} = F\,\hat{h}_{MMSE} = F\,R_{hy}R_{YY}{}^{-1}\,Y \tag{15}$$

Where,

$$R_{hy} = E\left(hY^H\right) = R_{hh}F^H X^H \tag{16}$$

$$R_{YY} = E\left(YY^H\right) = XFR_{hh}F^H X^H + \sigma_w^2 I_w \tag{17}$$

The term R_{hy} and R^{yy} are the cross covariance matrix between h and Y and the auto-covariance matrix of Y respectively. The term σ_w^2 represents the noise variance. The Least Square (LS) estimator is represented by [16]:

$$\hat{H}_{LS} = F\hat{h}_{LS} = FQ_{LS}F^H X^H Y \tag{18}$$

Where,

$$Q_{LS} = \left(F^H X^H XF\right)^{-1}, \tag{19}$$

Then the LS estimator becomes:

$$\hat{H}_{LS} = X^{-1}Y \tag{20}$$

5.2 Simplified Estimators

The MMSE estimator requires the calculation of an N x N matrix. The term *MMSE Q* implies a high complexity of MMSE design whenever N is large.

A simplified linear MMSE estimator with pilot signals is denoted as [17]:

$$\hat{H}_{LMMSE} = R_{hh}\left[Rhh + \frac{\beta}{SNR}\right]^{-1}\hat{H}_{LS} \tag{22}$$

Where, $SNR = E\left\{X_p(k)^2\right\}/\sigma_n^2$ (23)

$\beta = E\left\{X_p(k)^2\right\}E\left\{1/X_p(k)^2\right\}$ is the average signal-to noise ratio and a constant depending on the signal constellation.

5.3 Channel Estimation of OFDM Systems

This section presents the FFT-OFDM system that employs channel estimation technique (MMSE and LS) algorithms. Since the radio channel is frequency selective and time varying for wide band mobile communication systems, a dynamic estimation of channel is necessary for OFDM signals [18]. In order to estimate the channel transfer function, the inverse of the channel transfer function is applied to every OFDM frame. This compensates the channel effects very much like equalization technique. There are two types of channel estimations used i.e. block type and comb-type pilot channel estimation techniques.

A. Block-Type Pilot Channel Estimation

In block-type channel estimation technique is performed by inserting pilot carriers in all sub-carriers of OFDM symbols. OFDM channel estimation pilots are transmitted periodically. The Block-type pilot channel estimation technique has been developed under the assumption of slow fading channels [19], as shown in Figure 5.

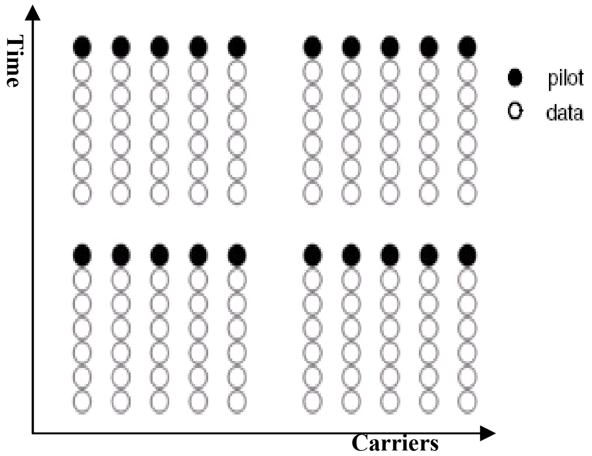

Figure 5: Block-type pilot Arrangement for OFDM Channel Estimations [19]

The estimation of the channel can be performed by using either LS or MMSE algorithms [19]. For LS, the estimated channel frequency response is given by:

$$H_e = X^{-1} \cdot Y \quad (24)$$

where X and Y denote the input data to IFFT block at the transmitter and the output data of FFT block at the receiver respectively.

The estimated channel frequency response (H_e) is used to find the estimated transmitted signal $X_e(k)$:

$$X_e(k) = Y(k) / H_e(k) \quad ,k = 0,1,\ldots,N-1 \quad (25)$$

When the channel is in slow fading, the channel estimation inside the block can be updated using the decision feed back equalizer at each sub-carrier [18].

B. Comb-Type Pilot Channel Estimation

The comb-type pilot channel estimation has been introduced whenever the channel changes fast, even in one OFDM block. This is done in order to satisfy the need for channel equalization. This technique estimates the channel at pilot frequency and interpolates the channel for the block of data as shown in Figure 6 [19].

The N_p pilot signals are uniformly inserted into $X(k)$ according to the following equation [19];

$$X(k) = X(mL+l) = \begin{cases} X_p(m), l=0 \\ \text{inf.data}, l=1,\ldots\ldots,L-1 \end{cases} \quad (26)$$

Where the term L stands for the number of carriers/N_P and $X_p(m)$ represents the m^{th} pilot carrier. The term $H_P(k)$ is the channel frequency response at the pilot sub-carriers.

The channel estimation at pilot sub-carriers based on LS estimation is given by;

$$H_e(k) = \frac{Y_P(k)}{X_P(k)} \quad ,k = 0,1,\ldots,N_P - 1 \quad (27)$$

The terms $Y_P(k)$ and $X_P(k)$ are the received and transmitted signals at k^{th} pilot sub-carrier respectively.

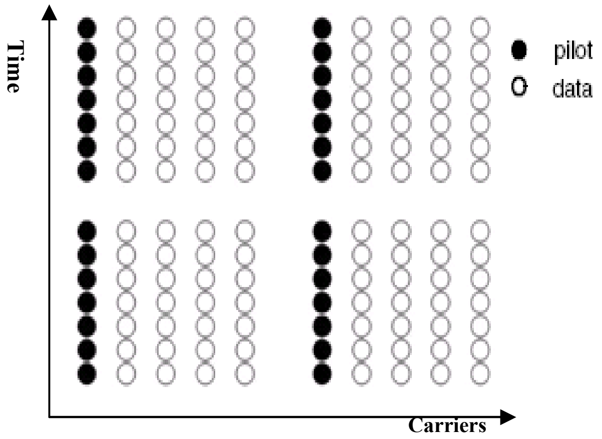

Figure 6: Comb-type pilot Arrangement for OFDM Channel Estimations [19]

In this simulation the number of sub-carriers Nc= 64, a cyclic prefix L = 4 have been chosen. The transmitted OFDM symbols are inserted with the pilot carriers.

The performance of the 64-subcarrier OFDM system the uses LS and MMSE algorithms are compared and the results are shown in Figure 7 based on the parameter of Mean square error (MSE). In this figure, the approximation effect is small as compared to the channel noise for low SNR, while it becomes dominant for larger SNR.

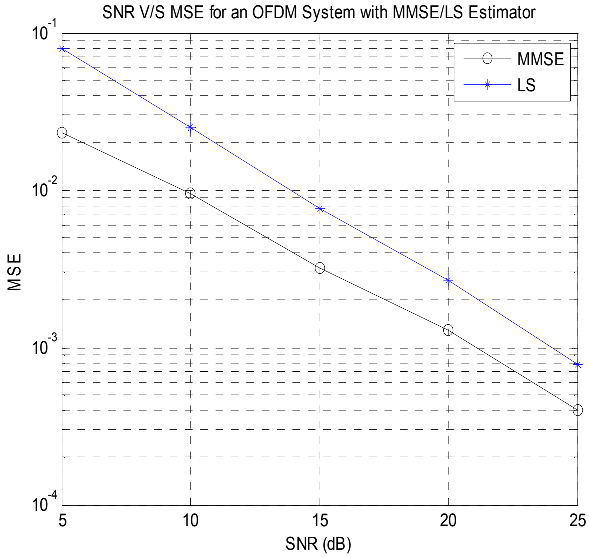

Figure 7: SNR V/S MSE for an OFDM System with MMSE/LS Estimator

The performance comparison of the LS and the MMSE channel estimators for a 64 subcarrier OFDM system based on the parameter of Symbol Error Rate (SER) as shows in Figure 8 . The SER curves presented are based on the mean-square errors (MSE) of the channel estimations.

For the calculation of SER, we have used the formulae presented in [20]. These formulae find the symbol error rate of the 64-QAM system given a noisy estimate of the channel. We consider in the decision-directed estimation without any error propagation.

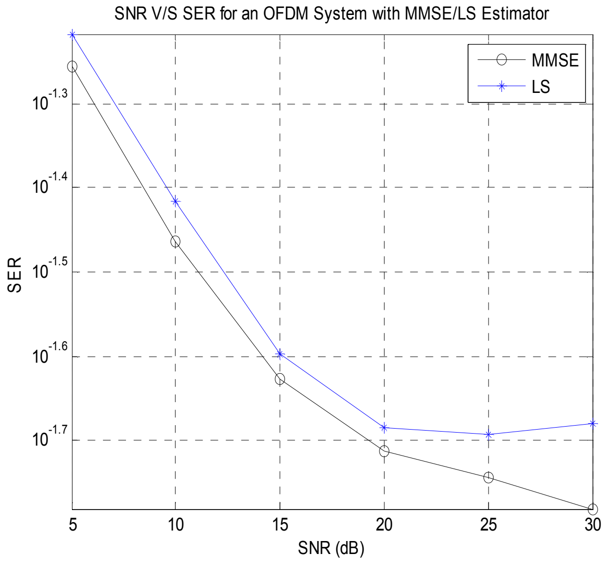

Figure 8: SNR V/S SER for an OFDM System with MMSE/LS Estimator

The SER versus the average SNR is plotted for the proposed block-type pilot channel estimation schemes over a slow fading channel, DFT size N = 64, and a cyclic prefix L = 4. In this figure, The MMSE estimator yields the best performance from LS.

6 Simulation Results

6.1 FFT and DWPT based OFDM

In this section simulation results are presented which show the performance comparison of DWPT-OFDM and FFT-OFDM in terms of BER in various wireless channels. The both FFT-OFDM and DWPT-OFDM systems are developed, analyzed, and simulated in Matlab version 7. The performance results of the system in AWGN channel, Flat Fading channel and Selective Fading channel are obtained using the OFDM parameters as listed in Table 1. The bit rate used in this simulation is 5 Mbps.

Table (1) Simulation Parameters

Parameter	OFDM	WPM
Data Rate	5Mbps	5Mbps
Modulation	QAM	QAM
No. of sub-carriers	32	32
No. of bits per Symbol	32	32
No. of FFT points	64	-
Wavelet	-	Haar
Channel Model	AWGN	
	Flat fading +AWGN	
	Frequency selective fading +AWGN	

A. BER Performance in FFT-OFDM at the AWGN Channel

The comparison is made of the FFT-OFDM between the QAM points of 8, 16, 32 and 64 over the AWGN channel. Simulation results are shown in Figure 9. The performance gain is wide between the systems that use 8 QAM points to the system with 64 points for higher SNR values. Higher performance gains are also observed when the SNR increases.

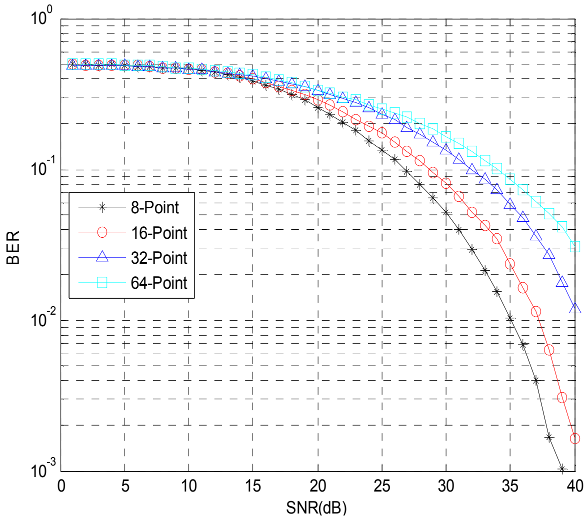

Figure 9: BER performance of FFT-OFDM in AWGN channel

B. BER Performance in DWPT-OFDM in AWGN Channel

Figure 10 shows results for the WPT-OFDM system that uses QAM points of 8, 16, 32 and 64 over AWGN channel. The performance gain is wide between the systems that use 8 QAM points to the system with 64 points for higher SNR values. Higher performance gains are also observed when the SNR increases.

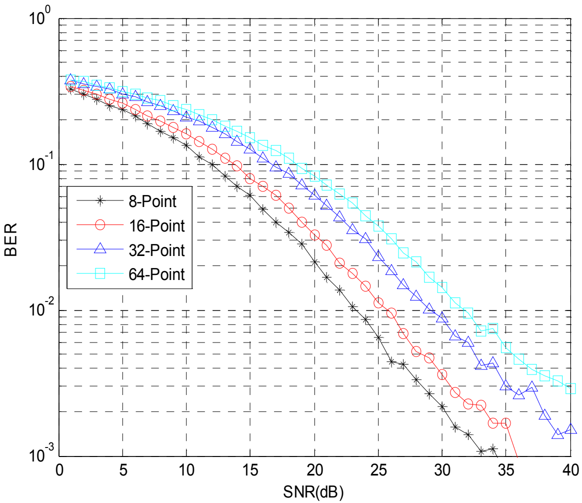

Figure 10: BER performance of DWPT-OFDM in AWGN channel

C. BER Performance between FFT-OFDM and DWPT-OFDM in AWGN channel.

The BER performance of the DWPT-OFDM system using QAM 8 constellation mapping points over AWGN channel is shown in Figure 11. The performance is better than the FFT-OFDM system at same QAM point.

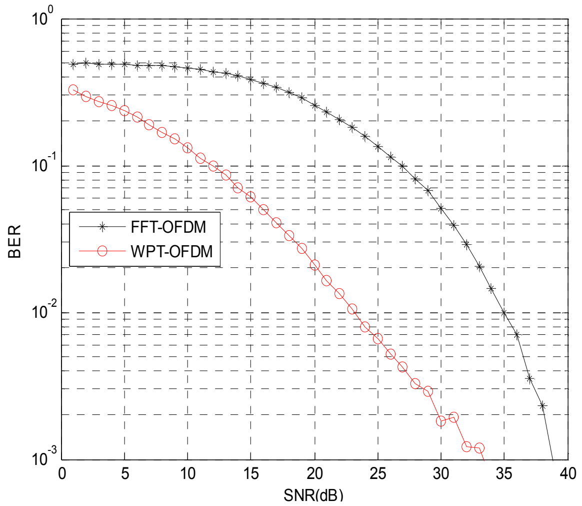

Figure 11: BER performance between FFT-OFDM & DWPT-OFDM in AWGN

D. BER Performance between FFT-OFDM and DWPT-OFDM in Flat Fading channel.

Figure 12 shows the BER performance of the DWPT-OFDM system using QAM 8 constellation mapping points over Flat Fading channel. From this figure it clearly shown that the performance of DWPT-OFDM is better than the FFT-OFDM system at same QAM point.

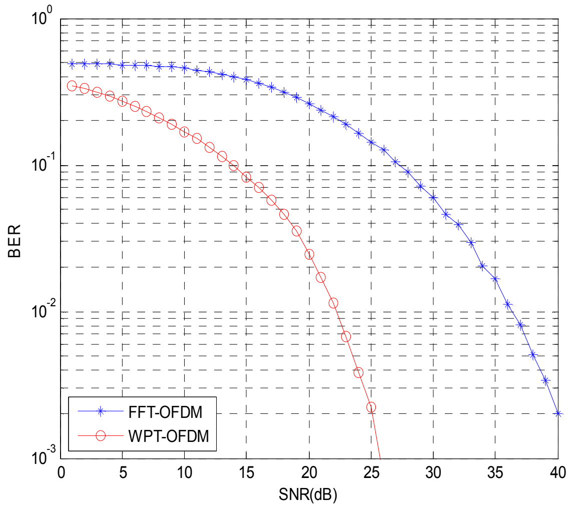

Figure 12: BER performance between FFT-OFDM&DWPT-OFDM in Flat Fading channel

E. BER Performance between FFT-OFDM and DWPT-OFDM (Selective Fading channel)

Figure 13, shows the performance comparison between the two systems under frequency selective fading channel. The BER performance has been obtained using QAM 8 constellation mapping points. This figure clearly shown that the DWPT-

OFDM system performance is better than the FFT-OFDM system.

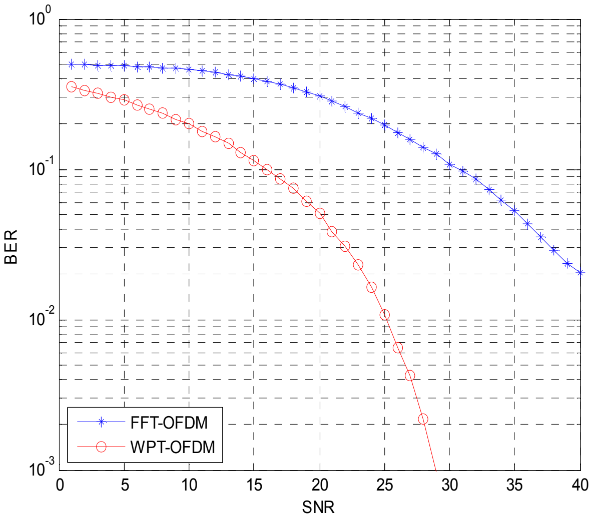

Figure 13: BER performance between FFT-OFDM &DWPT-OFDM in Selective Fading

In the Figures (11, 12 and 13) show the better performances of DWPT-OFDM as compared to FFT-OFDM system. FFT-OFDM exploits simple CP that greatly improves performance, but the performance will decrease when having synchronization error or due dispersive channel. The WPM as a consequence of the time overlap nature of its symbols cannot use CP or GI.

From figure 11 and figure 13, the DWPT-OFDM system always out performs FFT-OFDM system. This is due to the fact the FFT-based OFDM system uses a rectangular pulse shaping technique to replace the FFT-OFDM type of sinusoidal carrier that exhibits high side lobes. The high side-lobes in the transmitted signal increases OFDM system's sensitivity to ICI and introduce a Narrow-Band Interference (NBI). The WPM-based OFDM system provides better spectral shaping than FFT-based OFDM scheme. It offers much lower side lobes in the transmitted signal, which reduces ICI and NBI.

7 Conclusions

We present the performance analysis of DWPT-OFDM as alternative for FFT-OFDM in various fading channels. The results in terms of BER show that DWPT-OFDM system is superior to the traditional FFT-OFDM.

The performance of FFT-OFDM and DWPT-OFDM is also affected by the number of QAM points. Performance comparison in term of BER for both WPM and FFT OFDM systems over AWGN channel, Flat Fading channel and Selective Fading channel is carried out. In doing so various QAM points are used. The performance gain is wide between the systems that use 8 QAM points to the system with 64 points for higher SNR values. Higher performance gains are also observed when the SNR increases. Also in the DWPT-OFDM system, the BER performance at 8 point better than from 64 point. WPM and FFT modulation for OFDM system have nearly the same complexity according to the number of carriers. However, wavelets allow more flexibility in the system design. The performance results indicate that WPM is a viable alternative to OFDM but at the cost of higher complexity of equalization. Although, FFT-OFDM offers a low complexity structure than DWPT-OFDM, however, the use of CP reduces its spectral efficiency and wastes transmit power.

Acknowledgments

This work is funded in USM fellowship, USM-RU-PRGS, and USM RU grant with Grant Number 814012.

Authors Biography

Haitham J. Taha: received the Bachelor's degree, and Msc degree in Electronics and Communication Engineering from the University of Technology Baghdad, Iraq. He is Lecturer in the Department of Electrical and Electronic Engineering, University Of Technology. He has published papers in national and international journals and conferences. His teaching and research interest include digital communication, OFDM systems, signal processing. Currently, he is pursuing towards Ph.D. degree in Wireless Mobile System in School of Electrical and Electronic Engineering, Universiti Sains Malaysia. He works also as reviewer in an International Journal and he had been as reviewer in international conferences.

Mohd Fadzli, Mohd Salleh: was born in Bagan Serai, Perak, Malaysia. He received his B.Sc. degree in Electrical Engineering from Polytechnic University, Brooklyn, New York, U.S., in 1995. He was then a Software Engineer at MOTOROLA Penang, Malaysia, in R&D

Department until July 2001. He obtained his M.Sc. degree in Communication Engineering from UMIST, Manchester, U.K., in 2002. He obtained his Ph.D. degree in image and video coding for mobile applications, in June 2006 from the Institute for Communications and Signal Processing (ICSP), University of Strathclyde, Glasgow, U.K. Currently, he is working as a senior lecturer in the School of Electrical and Electronic Engineering, Universiti Sains Malaysia.

References:

[1] V. Kumbasar and O. Kucur, "Better wavelet packet tree based OFDM for multipath powerline channel", *Computers Electrical Engineering Journal,* Elsevier Ltd., doi:10.1016/j. compeleceng.2009.04.001, 2009.

[2] S. Baig, F.-ur-Rehman, M. J. Mughal, "Performance Comparison of DFT, Discrete Wavelet Packet and Wavelet Transforms, in an OFDM Transceiver for Multipath Fading Channel", *in Proc. 9th International Multitopic Conference, INMIC'05, 2005,* pp. 1-6.

[3] H. Zhang, D. Yuan, M. Jiang,and D. Wu, "Research of DFT-OFDM and DWT-OFDM on Different Transmission Scenarios", *in Proc ICITA'04, 2004*, pp.31-33.

[4] F. Farrukh, S. Baig and M.J. Mughal, "Performance Comparison of DFT-OFDM and Wavelet-OFDM with Zero-Forcing Equalizer for FIR Channel Equalization", ", *in Proc International Conference Electrical Engineering, ICEE'07, 2007,* pp. 1-5.

[5] D.Karamehmedovic, M. K. Lakshmanan and H. Nikookar, "Performance of Wavelet Packet Modulation and OFDM in the Presence of Carrier Frequency and Phase Noise", *Proceedings of the 1st European Wireless Technology Conference, EuMA*, Amsterdam, Netherlands, 2008, pp. 166-169.

[6] U. Khan, S. Baig and M. J. Mughal, "Performance Comparison of Wavelet Packet Modulation and OFDM for Multipath Wireless Channel", *International Conference Computer, Control and Communication*, Karachi, 2009, pp. 1-4.

[7] D. Gupta, V. B Vats and K. K. Garg, "Performance Analysis of DFT-OFDM, DCT-OFDM, and DWT-OFDM Systems in AWGN Channel", *IEEE Fourth International Conference Wireless and Mobile Communications,(ICWMC '08),* Athens, 2008, pp. 214-216.

[8] G. L. Stüber, *Principles of Mobile Communication*, Second Edition, Georgia Institute of Technology, Atlanta, Georgia, USA, 2002.

[9] P. Jain, "On the Impact of Channel and Channel Quality Estimation on Adaptive Modulation," *Msc. Thesis, Faculty of the Virginia Polytechnic Institute and State University, 2002.*

[10] S. Hara and R. Prasad, *Multicarrier Techniques for 4G Mobile Communications*, Artech House, Boston, 2003.

[11] L. Hanzo, M. Munster, B. J.Chol, and T. Keller, *OFDM and MC-CDMA for Broadband Multi-user Communications, WLANs and Broadcasting*, John Wiley & Sons 2003.

[12] Hongbing Zhang, "Wavelet Packet Based Multicarrier CDMA Wireless Communication Systems," *Ph.D. Thesis, University of Cincinnati USA*, 2004.

[13] Kenneth Hetling, "A PR-QMF (wavelet) based spread spectrum communications system," *in Proc. of MILCOM'94*, vol. 3, 1994, pp. 760-764.

[14] A. R. S. Bahai, B. R. Saltzberg, *Multi-Carrier Digital Communications: Theory and Application of OFDM*, Kluwer Academic/Plenum, 1999.

[15] Sarah Kate Wilson, R. Ellen Khayata and John M. Cioffi, "16-QAM modulation with orthogonal frequency-division multiplexing in a Rayleigh- fading environment", *in Proceeding VTC-1994, pp. 1660-1664, Stockholm, Sweden, June 1994.*

[16] He Chunlong, Hao Li. "Pilot-Aided Channel Estimation Techniques in OFDM System", *International Conference on Communication Software and Networks*, pp.143-146, 2009.

[17] O. Edfors, M. Sandell, J. -J. van de Beek, et al.,"OFDM channel estimation by singular value decomposition", *IEEE Transaction on Communication*s, vol.46, July 1998, pp. 931-939.

[18] Le Chung Tran, "Complex Orthogonal Space-Time Processing in Wireless Communications," *Ph.D. Thesis, University of Wollongong, Australia*, May 3, 2006.

[19] K. P. Bagadi and S. Das, "MIMO-OFDM Channel Estimation Using Pilot Carries", *International Journal of Computer Applications*, Vol 2, No.3, pp.81-88, May 2010.

[20] Sarah Kate Wilson, Digital Audio Broadcasting in a Fading and Dispersive Channel, *PhD-thesis, Stanford University*, August 1994.

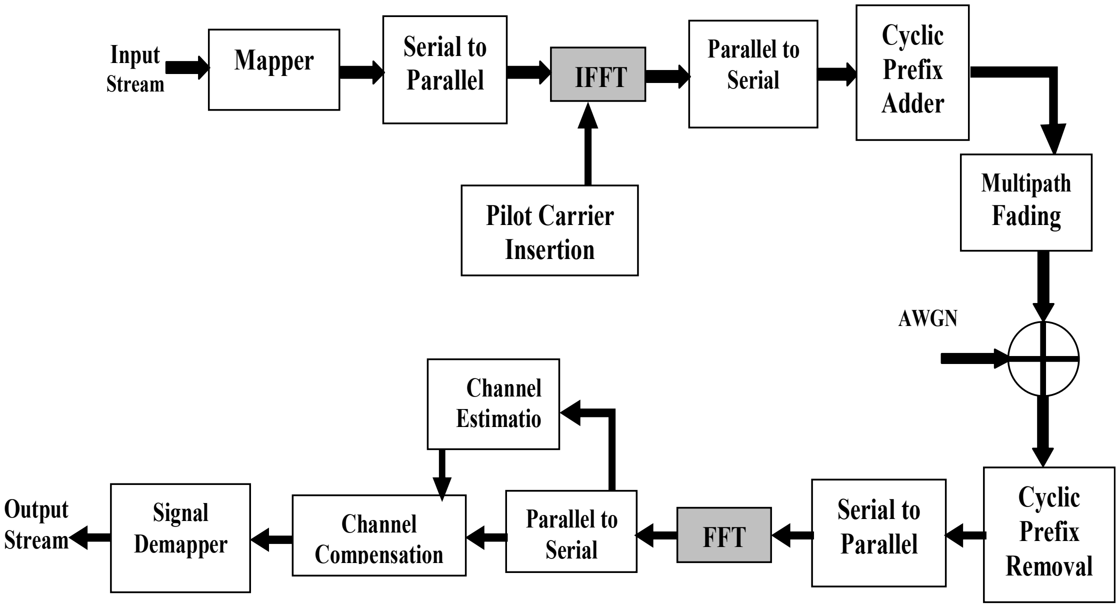

Figure 1: Block diagram of OFDM-FFT [10].

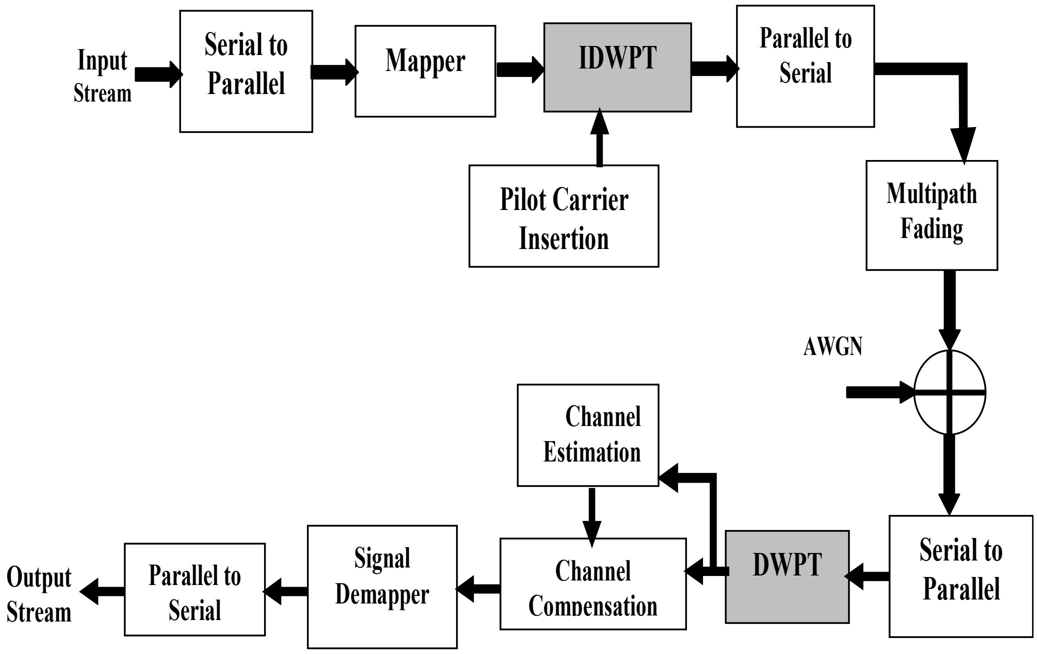

Figure 3: Block diagram of DWPT-OFDM.