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A Comparative Performance Analyses of FFT Based OFDM and DWT Based OFDM Systems

Engin ÖKSÜZ[1] (enginksz@hotmail.com)
Ahmet ALTUN (ahmtt.93@gmail.com)
Büşra ÜLGERLİ (busraulgerli@gmail.com)
Gökay YÜCEL (gokayyucel38.gy@gmail.com)
Ali ÖZEN (aozen@nny.edu.tr)

Nuh Naci Yazgan University - HARGEM
Department of Electrical and Electronics Engineering, 38010 Kayseri, Turkey.

Abstract – While continuously increasing demand for high data rates, to develop more efficient wireless communication systems will always be needed. Orthogonal Frequency Division Multiplexing (OFDM) is a promising multi-carrier wireless communication system for high-speed data transmission with spectral efficiency and fading immunity. Conventional OFDM systems use Fourier filters with the help of the inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) for modulation and demodulation in transmitter and receiver, respectively. On the other hand, wavelet based OFDM system uses orthonormal wavelets which are derived from a multistage tree-structured wavelet family. Discrete wavelet transform (DWT), reducing inter symbol interference (ISI) and inter carrier interference (ICI), can be used due to better orthogonality and more bandwidth efficiency for OFDM systems. In this paper, performance of the OFDM system based on low complexity DWT (DWT-OFDM) has been compared with FFT based OFDM (FFT-OFDM) system. In DWT based OFDM system, the IFFT and FFT blocks in conventional FFT based OFDM system are simply replaced by an IDWT and DWT, respectively. Computer simulations have been performed to verify the effectiveness of both methods and compare the performance of the DWT-OFDM and FFT-OFDM system in additive white Gaussian noise (AWGN) channel and AWGN plus frequency flat Rayleigh fading channels for different modulation types. The obtained simulation results using HIPERLAN/2 standard have demonstrated that the DWT-OFDM system has considerably better performance than the conventional FFT-OFDM system in all modulation types and also provides high SNR improvement of approximately 6 dB for a BER value of 1E-3.

Keywords *- FFT-OFDM, DWT-OFDM, ISI, ICI, bandwidth efficiency.*

[1]***Corresponding Author***

1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) system is a multi-carrier system that uses parallel processing techniques allowing data simultaneous transmission over very closely spaced orthogonal subcarriers. Conventional OFDM system uses inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) in the transmitter and the receiver respectively for simultaneous parallel multiplexing of signals in the transmitter and the receiver [1]. However, the main disadvantage of FFT is using a rectangular window, which creates rather high sidelobes. Moreover, the pulse shaping function used to modulate each subcarrier extends to infinity in the frequency domain. This leads to high interference and lower performance levels. Inter symbol interference (ISI) and inter carrier interference (ICI) can be avoided by adding a cyclic prefix (CP) to the beginning of the OFDM symbol. However, adding CP can largely reduce the spectrum efficiency. In the field of wireless communication, frequency resource increasingly tense, this is a problem to be considered.

The wavelet transform (WT) system has a higher spectral efficiency and providing robustness with regard to ISI and ICI than the conventional OFDM system, because of the out-of-band energy (low sidelobes) [2]. The basic theory of conventional OFDM and DWT-OFDM system share many similarities in terms of their functions. Both of these techniques have orthogonal sub-carriers, the overlapping of which makes them spectrally efficient [3-5]. But at the same time, they have also some distinctive features that make them different from each other. In conventional OFDM system, sub-carriers overlap in frequency domain, whereas in DWT-OFDM system, sub-carriers overlap in both time and frequency domain [2-5]. Overlapping in time domain is due to the fact that the waveforms used in DWT-OFDM system are longer than the transform duration of one symbol. DWT-OFDM symbols fulfil the property of double shift orthogonality and therefore, their overlapping does not cause ISI and does not require CP [3-5]. Hence, making DWT-OFDM system more bandwidth efficient compared to conventional OFDM system [3-5]. Fourier and wavelet transforms are almost the same in performing their tasks because they decompose signals into elementary waveforms or basis of frequency components. However, their basis functions are different. OFDM uses Fourier bases which are static sines/cosines as its elementary functions while DWT - OFDM uses wavelet packet bases derived from a class of perfect reconstruction filters called low pass and high pass filter coefficients. Due to the characteristics of the basis functions, wavelet has the ability to analyze the local properties of the input signal, such as edges or transients. In this case, Fourier transform is not an efficient tool to analyze the local property such as the edge or transient. In addition, the wavelet transform has time-frequency local property, the power difference of its main-lobe and vice-lobe is 45dB, so it can well suppress side lobe without adding the window, thereby reducing the effect of inter symbol interference [5]. Additionally, WT provides the time-frequency representation of signals, whereas discrete Fourier transform (DFT) gives only the frequency representation. The properties of wavelet, such as localization in time and frequency, orthogonality across scale and translation presents to a new perspective in digital communication.

Wavelet transform emerged in recent years is a strong candidate for digital modulation [6, 7]. There are many studies available due to the aforementioned advantages of wavelet transform in wireless communications. Among them: Discrete Wavelet Transform based OFDM (DWT - OFDM) was first proposed in 1997 by Lindsay as an alternative to FFT based OFDM scheme [8]. Wornell and Oppenheim outlined the design of the transmitter and receiver for wavelet modulation [9]. The performance of wavelet modulation in additive white Gaussian noise (AWGN) channel was also evaluated in Wornell's work [9]. Haixia Zhag et al. based on their work titled "Research of Discrete Fourier Transform based OFDM (DFT-OFDM) and Discrete Wavelet Transform Based OFDM (DWT-OFDM) on Different Transmission Scenarios" concluded that DWT-OFDM performs much better than DFT-OFDM. But they observed an error floor in DWT- OFDM systems [10]. Akansu et al. emphasize the relation between filter banks and trans-multiplexer theory and predict that wavelet packet based modulation has a role to play in future communication systems [11]. Dereje Hailemariam in his thesis work titled "Wavelet Based Multicarrier Code Division multiple Access Communication (MC-CDMA) for wireless Environment" investigated the performance of MC-CDMA in three transmission scenarios and in his direction to future work he predicts designing of wavelet filters which are better suited to OFDM left as an area to be explored [12]. B. G. Negash and H. Nikookar on their paper wavelet based OFDM for wireless channels reached to results wavelet based multicarrier highly reduce ICI and ISI powers and stressed the non-uniform division of the transmission bandwidth by this modulation technique makes it more attractive for future application dependent OFDM services [13]. Antony Jamin and Petri Mahonen on the article wavelet packet modulation for wireless communications concluded the performance results of the new modulation scheme: wavelet packet modulation is a viable alternative to conventional OFDM and they stressed the best method to be used in order to select suitable wavelets is a topic to be studied further [14]. Among other uses of wavelets are source and channel coding, channel modeling, data compression, signal denoising, and design of transceivers. It is reported that the flexibility and ability to characterize signals accurately is the main property of wavelets in these applications. Having such property makes wavelets a strong candidate for future use in the wireless field [15, 16].

In this paper, an OFDM system based on low complexity DWT has been presented. In DWT based OFDM system, the IFFT and FFT blocks in conventional FFT based OFDM system are simply replaced by an IDWT and DWT, respectively. Computer simulations have been performed to compare the performance of the DWT-OFDM and FFT-OFDM system in AWGN channel and AWGN plus frequency flat Rayleigh fading channels for different modulation types. The obtained simulation results have demonstrated that the DWT-OFDM system has considerably better performance than the conventional FFT-OFDM system in all modulation types and also provides high SNR improvement of approximately 6 dB for a BER value of 1E-3.

The remaining of the paper is organized as follows: Section 2 summarizes conventional FFT-OFDM system employed in simulations. The DWT-OFDM system is introduced in detail in Section 3 and 4. Section 5 evaluates the obtained performances to verify the feasibility and robustness of the presented technique and finally, the paper is concluded in Section 6.

2 Fast Fourier Transform Based OFDM (FFT – OFDM)

Figure 1 has shown the block diagram of FFT/DWT–OFDM transceiver system [17, 18], where inverse and forward transform blocks are related to FFT–OFDM or DWT–OFDM. Because FFT–OFDM system is well known in literature, it will be given short summary here.

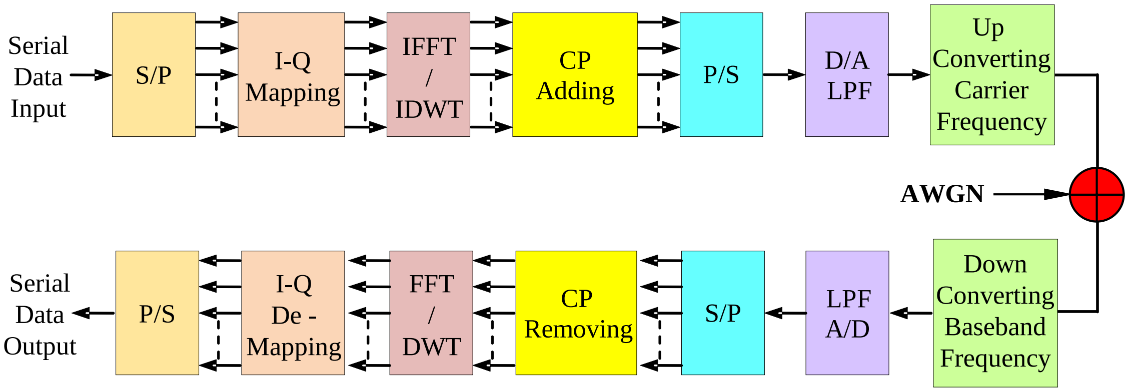

Figure 1. The block diagram of FFT/DWT – OFDM system [17, 18].

Once converted to parallel data arriving serially from the source, depending on the numbers of bits sent by the sub-carriers are divided into groups with the help of I-Q matching. 4-QAM, 16-QAM and 64-QAM modulation is used for this study. While 48 sub-carriers are carrying data in an OFDM symbol, 4 sub-carriers are also used as a pilot. The 12 sub-carriers are transmitted as an empty. Accordingly, frequency domain samples, consisting of 64 complex samples, are obtained. Then time domain samples are obtained with the help of the IFFT. Let the *n*-th OFDM symbol contain N coded QAM symbols in a complex data vector represented as $b_n = \left[b_{n,0} \;\; b_{n,1} \;\; b_{n,2} \;\; \dots \;\; b_{n,N-1}\right]^T$. The output of the IFFT block is $d_n = \left[d_{n,0} \;\; d_{n,1} \;\; d_{n,2} \;\; \dots \;\; d_{n,N-1}\right]^T$ which is defined as:

$$d_n(k) = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} b_{n,i}\, exp\left(j\frac{2\pi}{N}ik\right), \quad k = 0, 1, 2, \dots, N-1 \tag{1}$$

where 'T' indicates the process of transpose, $d_n(k)$, time domain signal and $D_{n,i}$, modulated complex datas in the output of I-Q mapping block will be fed to sub-carriers. The copied last 16 examples of the time domain samples are added to the beginning part of the data packet in order to mitigate inter-symbol interference. This is further extended by adding a cyclic prefix as explained below. The CP is a guard time between consecutive OFDM symbols and helps to obtain ISI-free time samples for each OFDM symbol in the receiver. An OFDM symbol, composed of a total of 80 samples with by adding the 16 samples, is obtained.

Let N_{CP} (16 in this case) represent the number of samples in the cyclic prefix. This data is added to beginning of the OFDM symbol in order to provide the required guard time. The time domain sequence for the n-*th* symbol, $x_n(i)$, $(i = -N_{CP}, \; -N_{CP}+1, \dots, \; 0, 1, \dots, \; N-1)$ is defined by:

$$x_n(i) = \begin{cases} d_n(N+i), & i = -N_{CP}, \dots, -1 \\ d_n(i), & i = 0, \dots, N-1 \end{cases} \tag{2}$$

Then the amplified signal, up converted 5 GHz band, is issued to antenna [1].

The transmission medium is represents by a multipath time dispersive channel. The Tapped Delay Line (TDL) filter coefficients are represented by $h = [h_0 \;\; h_1 \;\; h_2 \;\; \dots \;\; h_{L-1}]^T$, where L is the number of taps in the model. The output of the channel is given below in matrix form:

$$v_n = x_n * h + w_n \tag{3}$$

or alternatively in the form of a discrete time sequence:

$$v_n(k) = \sum_{l=0}^{L-1} h_l\, x_n(k-l) + w_l \tag{4}$$

where '*' indicates the process of convolution and $w = [w_0\ w_1\ w_2\ \dots\ w_{N-1}]^T$ is the white Gaussian noise sequence added to the N samples on reception. These can be considered as the noise sequence added to the received data after the removal of the guard interval. The frequency domain received sequence becomes:

$$y_n(k) = \sum_{i=0}^{N-1} v_n(i)\, exp\left(-j\frac{2\pi}{N}ik\right) = \sum_{i=0}^{N-1}\left[\sum_{l=0}^{L-1} h_l x_n(i-l) + w_i\right] exp\left(-j\frac{2\pi}{N}ik\right) \tag{5}$$

A reorganizing of Equation (5) leads to:

$$\begin{aligned} y_n(k) &= \sum_{i=0}^{N-1}\sum_{l=0}^{L-1} h_l exp\left(-j\frac{2\pi}{N}li\right) x_n(i-l) exp\left(-j\frac{2\pi}{N}(i-l)k\right) \\ &\quad + \sum_{i=0}^{N-1} w_i\, exp\left(-j\frac{2\pi}{N}ik\right) \\ &= \sum_{l=0}^{L-1} h_l exp\left(-j\frac{2\pi}{N}lk\right) \sum_{i=0}^{N-1} x_n(i-l) exp\left(-j\frac{2\pi}{N}(i-l)k\right) \\ &\quad + \sum_{i=0}^{N-1} w_i\, exp\left(-j\frac{2\pi}{N}ik\right) \end{aligned} \tag{6}$$

where the functional component exp $\left(-j\frac{2\pi}{N}ik\right)$ has a period of N. Therefore, it can be written as

$$\text{exp}\ \left(-j\frac{2\pi}{N}ik\right) = \text{exp}\ \left(-j\frac{2\pi}{N}(i+N)k\right) \tag{7}$$

Given the structure of an OFDM symbol, $L < N_{CP}$ and, for $l = 1, 2, \dots, L$, it is also known that $x_n(-l) = x_n(N-l)$ and Equation (6) becomes:

$$\begin{aligned} &\sum_{i=0}^{N-1} x_n(i-l)\, exp\left(-j\frac{2\pi}{N}k(i-l)\right) \\ &= \sum_{i=-l}^{-1} x_n(i) exp\left(-j\frac{2\pi}{N}ik\right) + \sum_{i=0}^{N-1-l} x_n(i) exp\left(-j\frac{2\pi}{N}ik\right) \\ &= \sum_{i=N-l}^{N-1} x_n(i) exp\left(-j\frac{2\pi}{N}ik\right) + \sum_{i=0}^{N-1-l} x_n(i) exp\left(-j\frac{2\pi}{N}ik\right) \\ &= \sum_{i=0}^{N-1} x_n(i) exp\left(-j\frac{2\pi}{N}ik\right) = b_n(k) \end{aligned} \tag{8}$$

Equation (7) is now transformed to:

$$\sum_{l=0}^{L-1} h_l\ \text{exp}\ \left(-j\frac{2\pi}{N}lk\right) = \sum_{i=0}^{N-1} h_i\ \text{exp}\ \left(-j\frac{2\pi}{N}ik\right) = H_k \tag{9}$$

When H_k represents the frequency domain k-th coefficient of the channel h, and $h_i = 0$ for $i = L, \ldots, N-1$, and Equation (8) can be written as:

$$y_n(k) = H_k b_n(k) + W_k \tag{10}$$

where W_k is the k-th sample of the noise component w in the frequency domain, which remains after the FFT operation. The matrix form of this equation is written as:

$$\begin{bmatrix} y_n(0) \\ y_n(1) \\ \vdots \\ y_n(N-2) \\ y_n(N-1) \end{bmatrix} = \begin{bmatrix} H_0 & 0 & \cdots & 0 & 0 \\ 0 & H_1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & H_{N-2} & 0 \\ 0 & 0 & \cdots & 0 & H_{N-1} \end{bmatrix} \begin{bmatrix} b_n(0) \\ b_n(1) \\ \vdots \\ b_n(N-2) \\ b_n(N-1) \end{bmatrix} + \begin{bmatrix} W_0 \\ W_1 \\ \vdots \\ W_{N-2} \\ W_{N-1} \end{bmatrix} \tag{11}$$

The matrix H shows that intersymbol interference does not exist in the system. The short form of Equation (11) can be written as:

$$Y_n = Hb_n + W \tag{12}$$

where $W = [W_0 \;\; W_1 \;\; W_2 \;\ldots\; W_{N-1}]^T$ and $H = diag(H_k)$.

In recent years, digital communication technologies have become an integral part of our lives. Future wireless communication systems are expected to support a wide range of high-quality services that require high data rates. When communication channels are required to support higher data rates, signal distortions due to channel fading, noise, inter-symbol-interference (ISI), carrier frequency offset (CFO) and Doppler shift can limit the overall transmission data rate and coverage. In order to mitigate the effects of these impairments, several channel estimation and equalization methods have been developed in the last few decades. One of the best ways to cancel these effects is to use an equalizer filter that eliminates the ISI while combining the multipath energy [19–21]. In practice, linear transversal equalizers (LTE), decision feedback equalizers (DFE) and frequency domain channel equalizer (FDE) are the most common structures used in time domain and frequency domain respectively [22, 23]. To achieve this, good channel estimation and equalization algorithms are needed. The equalized signal is fed to decision mechanism. Finally, output data is obtained at the output of decision block and then the desired any performance comparisons are also performed [24].

3 Discrete Wavelet Transform (DWT)

The Wavelet Transform has recently gained a lot of popularity in the field of signal processing since it has the capability to provide both time and frequency information simultaneously, hence it gives a time-frequency representation of the signal. A wavelet is a small waveform that has effectively limited duration having an average value of zero. The wavelet analysis consists of breaking up a signal into scaled and shifted versions of the original signal or mother wavelet. Wavelets are a class of functions used to localize a given function in both space and scaling. A family of wavelets can be constructed from a function $\psi(t)$, sometimes known as a "mother wavelet," which is confined in a finite interval [25]. Daughter wavelets $\psi^{a,b}(t)$, are then formed by translation factor, b and contraction factor, a. Wavelets are especially useful for compressing image data, since a wavelet transform has properties which are in some ways superior to a conventional Fourier transform.

An individual wavelet can be defined by [25],

$$\psi^{a,b}(t) = |a|^{-1/2}\,\psi\left(\frac{t-a}{b}\right) \tag{13}$$

Then, the continuous wavelet transform (CWT) of a signal $x(t)$ is given by [17],

$$W_{\psi}(f)(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} x(t)\,\psi\left(\frac{t-b}{a}\right)dt \tag{14}$$

where a is the scaling factor and b is the translation factor.

The transform of the signal is just another form of representing the signal. In Fourier theory a signal can be represented as the sum of a possibly infinite series of sinusoids, which is referred to as a Fourier expansion. Fourier expansion works well with time invariant signals. For a time-varying signal, a complete characterization in the frequency domain should include the time aspect, resulting in the time-frequency analysis of a signal. In the past several solutions have been developed which are more or less able to represent a signal in the joint time-frequency domain, which include the short time Fourier transform (STFT) and wavelet transform [12, 26].

The topic of wavelets is multi-faceted and highly mathematical, and a subject that is arguably dominated by researchers with a mathematical background. It was developed to resolve the time frequency resolution problem of Fourier transform (FT) and STFT [27]. The FT does not provide a time-frequency representation of signal while a STFT causes uncertainty in the time-frequency representation [28]. The WT is the ultimate solution in representing the time-varying signal. It has a variable window, enabling it to provide a more flexible time and frequency resolution than STFT [27, 28]. The CWT produces coefficients for every scale up to a scale where one chooses to stop. Unfortunately this can lead to a significant amount of computational complexity and requires a reasonable amount of computational effort.

Computational complexity is too much in CWT. DWT is used to reduce the computational load. Wavelet transform, which separates data into different frequency components and analyzes each component with the resolution on that scale, is a conversion technique. Wavelet transform of a signal which is a function of time depends on frequency and time variables. The wavelets provide a good tool for time-frequency analysis [29].

Continuous wavelet transform, multiplied signal by shifted and scaled versions of the mother wavelet in the time domain is sum along of all the time. As a result of this process, the wavelet coefficients, depending on the location and scale, are obtained. If scaling and shifting is selected as two of the bases, analyses are more effective as to continuous wavelet and as accurate as continuous wavelet transform. This kind of analysis what is Discrete Wavelet Transform [30]. Discrete wavelet transform both reduces the computational load and provides sufficient information for the analysis and synthesis of the original signal. The basic idea of discrete wavelet transform is the same as the continuous wavelet transform. Representative of the time-scale of the digital signal using digital filtering techniques is obtained. Continuous Wavelet Transform specifies the relationship between signal and wavelet at different scales. Here, the criterion of similarity is scale or frequency.

DWT wavelets are transformation techniques with desirable characteristics of localization both in time and frequency. They also possess the property of orthogonality across scale and translation. The DWT provides a means of decomposing sequences of real numbers in a basis of compactly supported orthonormal sequences each of which is related by being a scaled and shifted version of a single function. The DWT of a signal $x(t)$ is the set of coefficients $X_{DWT}(m,k)$ for m and k obtained as the inner product of the signal $x(t)$ and the wavelet function, $\psi_{m,k}$. The discrete wavelet and inverse discrete representation of a signal $x(t)$ is given by equation (15) and (16) respectively.

$$X_{DWT}{}_{k}^{m} = \int_{-\infty}^{\infty} x(t)^{\frac{m}{2}} \psi(2^{m}t - k)dt \tag{15}$$

$$X_{IDWT}(t) = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} X_{k}^{m} \, 2^{\frac{m}{2}} \psi(2^{m}t - k) \tag{16}$$

4 Discrete Wavelet Transform Based OFDM (DWT - OFDM)

The block diagram of discrete wavelet transform based OFDM (DWT-OFDM) system is shown in figure 1. DWT-OFDM is an efficient approach to replace FFT in conventional OFDM systems. DWT is employed in order to remove the use of cyclic prefix which decreases the bandwidth wastage and the transmission power is also reduced by the use of wavelet transform. The spectral containment of the channels in DWT - OFDM is better than FFT-OFDM. In Wavelet transform, the signal of interest is decomposed into set of basis waveforms, known as wavelets, which provide the way for analyzing the signals by investigating the coefficients of wavelets. DWT is used in several applications and has become very popular among engineers, technologists and mathematicians. The basis functions of wavelet transform are localized both in time and frequency and possess different resolutions in both domains which makes the wavelet transforms a powerful tool in various applications. Different resolutions correspond to analyze the behaviour of the process and the power of the transform [15].

A low pass filter and high pass filter is employed to operate as quadrature mirror filter (QMF) and satisfies perfect reconstruction and orthonormal properties. In wavelet based OFDM, the modulated signal is transmitted using zero padding and vector transposing. DWT is known as a flexible and highly efficient method for decomposition of signals.

In this study, DWT transmitter and DWT receiver structure, shown in Figure 2 and Figure 3, is used in the obtained better BER-SNR performance on the DWT-OFDM system for AWGN channel and frequency flat Rayleigh fading channels [17, 18].

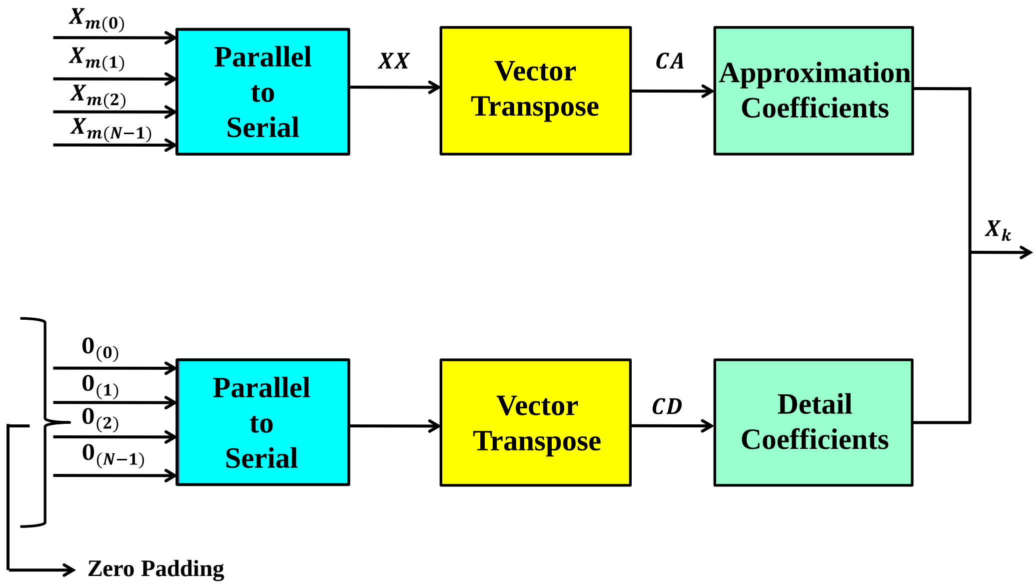

Figure 2. The block diagram of DWT – OFDM transmitter system [17, 18].

In the transceiver model shown in Figure.1, it is obvious that the transmitter first uses a M-QAM digital modulator (4-QAM, 16-QAM and 64-QAM) which maps the serial bits b_k into the OFDM symbols $X_{m(i)}$, within N parallel data stream $X_{m(i)}$ where $X_{m(i)}, 0 \leq i \leq N-1$. The main task of the transmitter is to perform the discrete wavelet modulation by constructing orthonormal wavelets. Each $X_{m(i)}$ is first converted to serial representation having a vector XX which will next be transposed into CA as shown in details as in Figure 2. This means that CA not only its imaginary part has inverting signs but also its form is changed to a parallel matrix. Then, the signal is up-sampled and filtered by the LPF coefficients or namely as approximated coefficients. This coefficients are also called scaling coefficients. Since our aim is to have low frequency signals, the modulated signals XX perform circular convolution with LPF filter whereas the HPF filter also perform the convolution with zero padding signals CD respectively. Note that the HPF filter contains detailed coefficients or wavelet coefficients. Different wavelet families have different filter length and values of approximated and detailed coefficients. Both of these filters have to satisfy orthonormal bases in order to operate as wavelet transform [15]. The number of CA and CD depends on the OFDM subcarriers N. Samples of this processing signals CA and CD that pass through this block model is shown in Figure 3. The above mentioned signals are simulated using MATLAB command $X_k = idwt(CA, CD, 'haar')$. The detailed and approximated coefficients must be orthogonal and normal to each other.

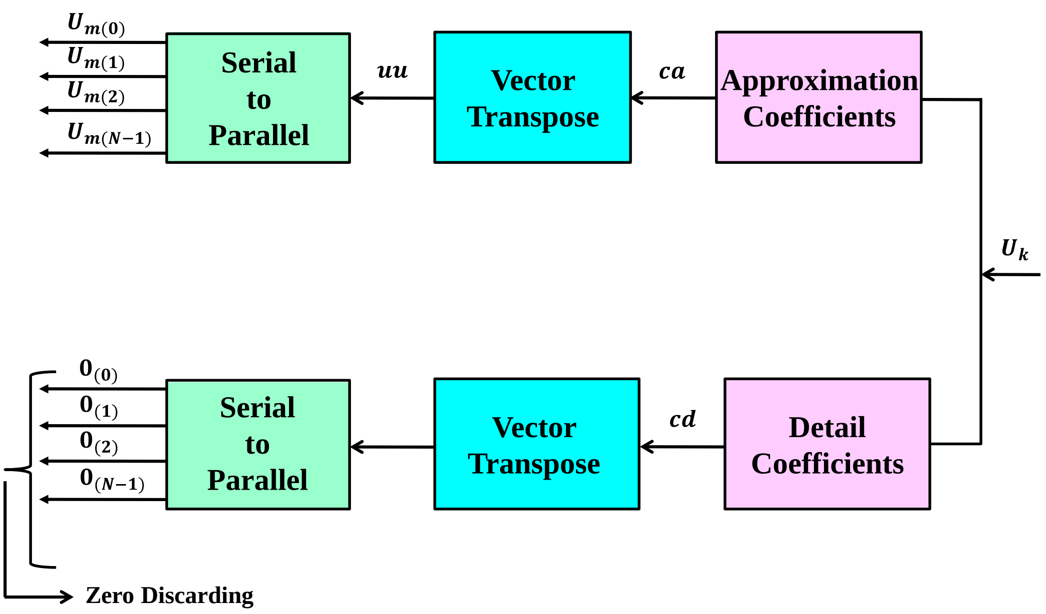

Figure 3. The block diagram of DWT – OFDM receiver system [17, 18].

The DWT receiver is the reverse process which is simulated using the MATLAB command $[ca, cd] = dwt(U_k, 'haar')$. The receiver system model that processes the data ca, cd and U_k is shown in Figure 3. The parameter 'haar' is to indicate the wavelet family that is used in this simulation. U_k is the front-end receiver data. This data is decomposed into two filters; high and low pass filters corresponding to detailed and approximated coefficients accordingly. The ca signal which is the output of the approximated coefficients or low pass filter will finally be processed to the M-QAM demodulator for data recovery [15]. In order to perform that operation, data is first transposed before converting into parallel representation. The output $U_{m(i)}$ is passed to M-QAM demodulator. The index i depends on the number of OFDM subcarriers. Due to the effect of CD data generated in the transmitter, U_k has some zeroes elements which is decomposed as the detailed coefficients. The signal output of these coefficients is cd. Comparing to ca, the cd signal is discarded because it does not contain any useful information.

5 Computer Simulation Results

The computer simulation studies have composed of two stages. In the first stage studies are performed using AWGN channel. In the second stage studies are also implemented employing AWGN and frequency flat Rayleigh fading channels. Bit error rate (BER) performances have been analyzed the FFT-OFDM and DWT-OFDM systems for two stages.

5.1 Simulation Results of AWGN Channel

In the first stage, BER versus SNR performance criteria has been used to compare the performance of conventional FFT-OFDM and DWT-OFDM systems over AWGN channel. The simulation studies have been obtained via 1000 Monte Carlo trails using 20 OFDM symbols for the 4-QAM, 16-QAM and 64-QAM modulation. The computer simulation studies have been performed using the physical layer specifications of IEEE 802.11a (HIPERLAN/2) standard [31, 32].

The obtained comparative BER versus SNR performances related to 4-QAM, 16-QAM and 64-QAM are given by Figure 4, 5 and 6, respectively.

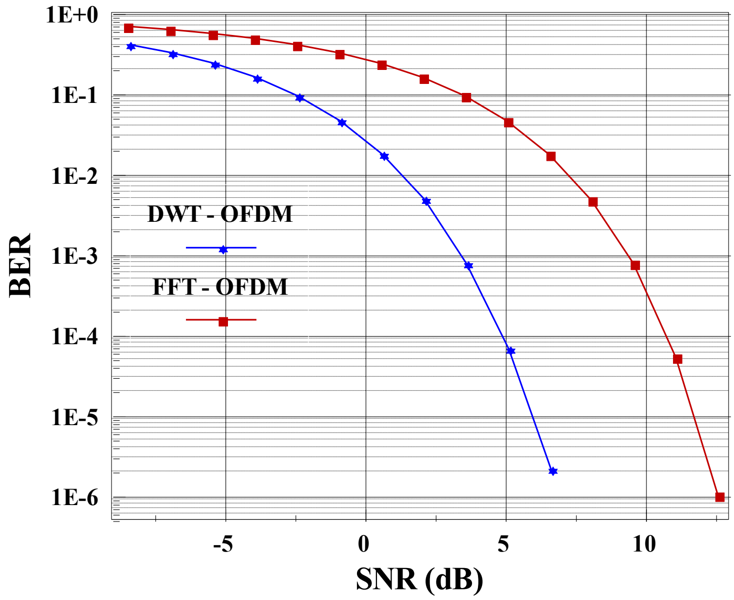

Figure 4. Comparison BER versus SNR performances of conventional FFT-OFDM and DWT-OFDM systems in AWGN channel for 4-QAM.

Figure 4 compares the BER performances of FFT-OFDM and DWT-OFDM for 4-QAM. It can be seen from Figure 4 the BER performance obtained using the DWT-OFDM technique outperforms the conventional FFT-OFDM and provides high SNR improvement of approximately 6 dB for a BER value of 1E-5. This can be explained by providing robustness with regard to ISI and ICI due to the out-of-band energy and higher spectral efficiency of wavelet transform. The performance improvement by the presented technique is very significant that, with little increase on the complexity, the conventional 4-QAM, 16-QAM and 64-QAM have become a high performance modulation technique with DWT.

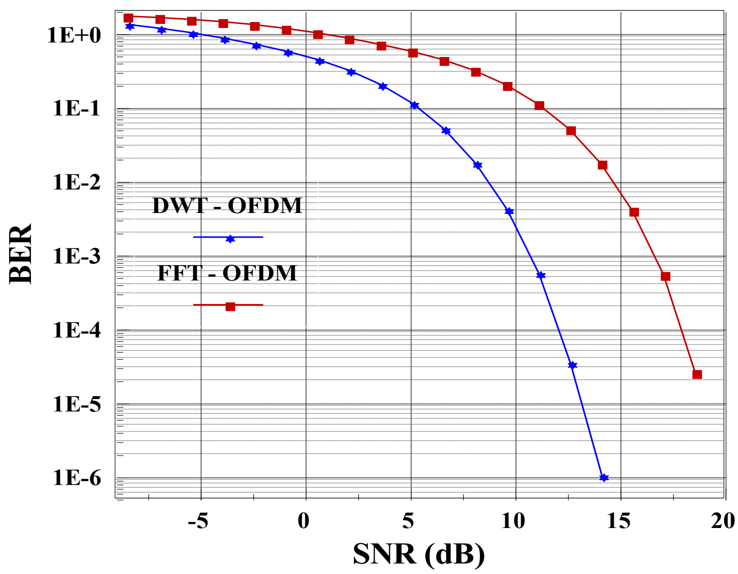

Figure 5. Comparison BER versus SNR performances of conventional FFT-OFDM and DWT-OFDM systems in AWGN channel for 16-QAM.

When the BER-SNR performances belong to the 16-QAM and 64-QAM modulation are investigated in Figure 5 and 6, similar performances are also obtained in 4-QAM modulation. The performance differences are protected between conventional FFT-OFDM and DWT-OFDM systems. Because only modulation depth increased, SNR values have changed.

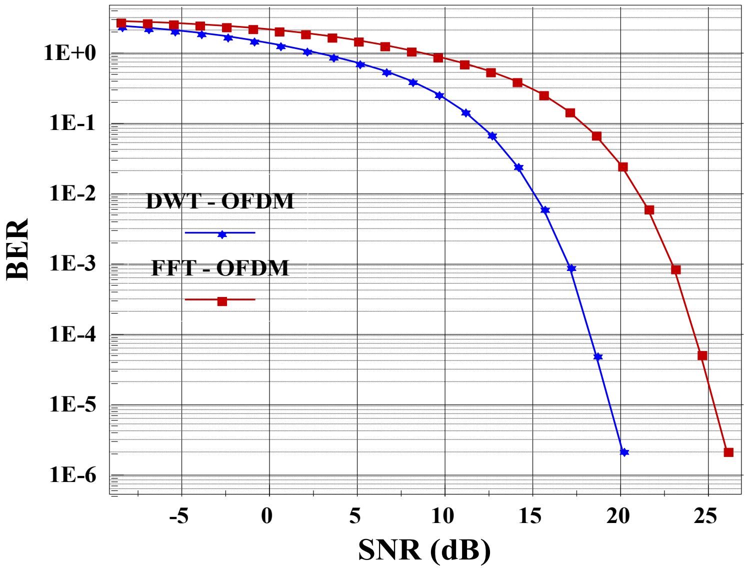

Figure 6. Comparison BER versus SNR performances of conventional FFT-OFDM and DWT-OFDM systems in AWGN channel for 64-QAM.

5.2 Simulation Results of AWGN and Frequency Flat Rayleigh Fading Channel

In the second phase, it is assumed that the received signal at the receiver is corrupted by AWGN and frequency flat Rayleigh fading channel in order to assess the performances of conventional FFT-OFDM and DWT-OFDM systems. The comparative performance analysis of the results of AWGN channel with AWGN and frequency flat Rayleigh fading channel have been performed via 10000 Monte Carlo loops using 20 OFDM symbols for the same modulation types.

The obtained comparative BER versus SNR performances belong to 4-QAM, 16-QAM and 64-QAM are given by Figure 7, 8 and 9, respectively.

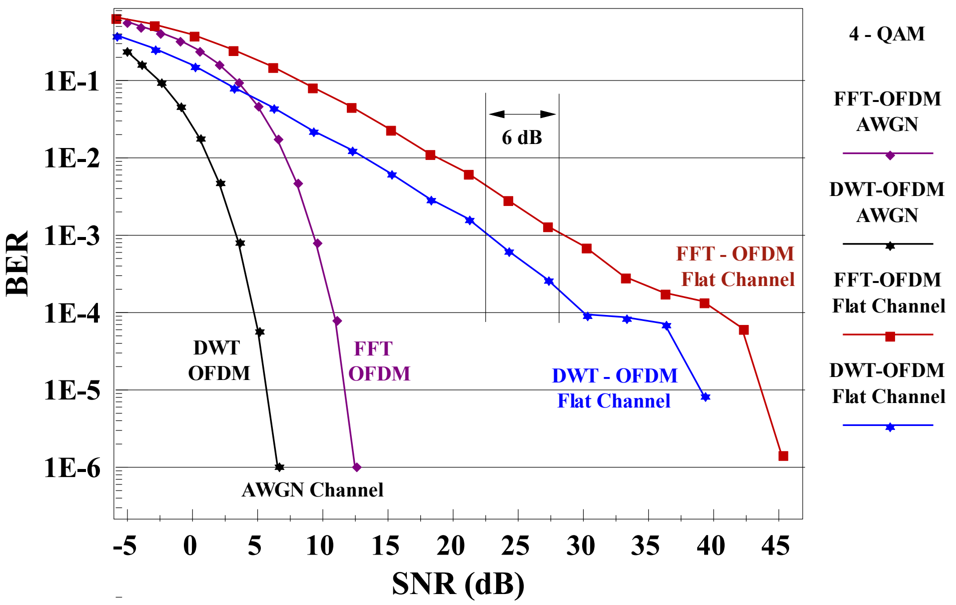

Figure 7. Comparison BER versus SNR performances of conventional FFT-OFDM and DWT-OFDM systems in AWGN channel with AWGN and frequency flat Rayleigh fading channel for 4-QAM.

Figure 7 compares the BER performances of FFT-OFDM and DWT-OFDM in AWGN channel with AWGN and frequency flat Rayleigh fading channel for 4-QAM. It can be seen from Figure 7 the BER performance obtained using the DWT-OFDM technique outperforms the conventional FFT-OFDM and provides high SNR improvement of approximately 6 dB for a BER value of 1E-3.

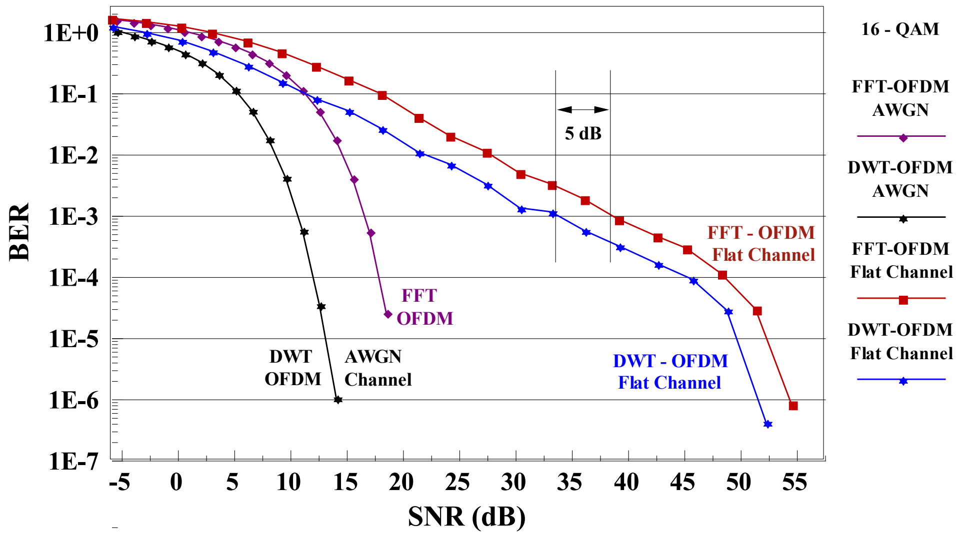

Figure 8. Comparison BER versus SNR performances of conventional FFT-OFDM and DWT-OFDM systems in AWGN channel with AWGN and frequency flat Rayleigh fading channel for 16-QAM.

When the comparison BER-SNR performances about AWGN and frequency flat Rayleigh fading channel belong to the 16-QAM modulation is investigated in Figure 8, it can be seen that DWT-OFDM system provides high SNR improvement of approximately 5 dB for a BER value of 1E-3.

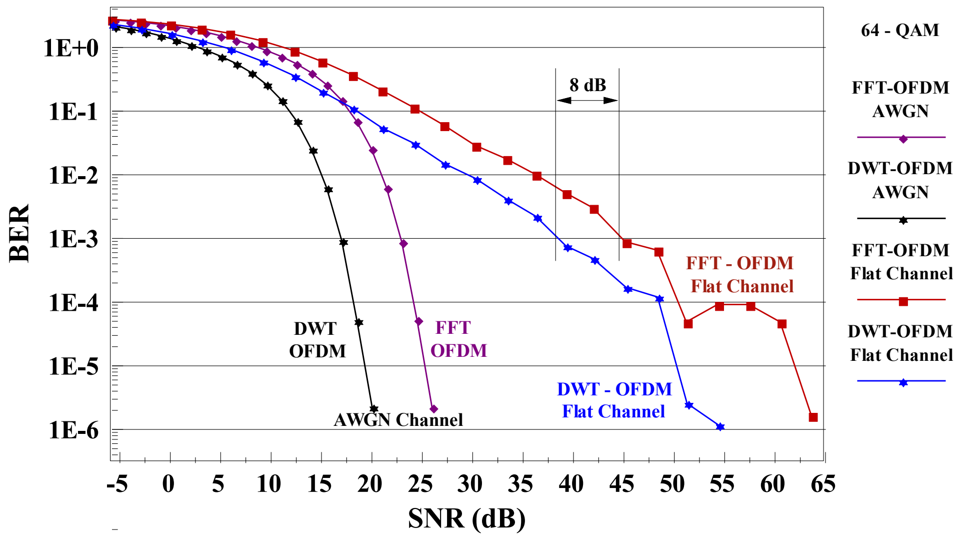

Figure 9. Comparison BER versus SNR performances of conventional FFT-OFDM and DWT-OFDM systems in AWGN channel with AWGN and frequency flat Rayleigh fading channel for 64-QAM.

When the comparison BER-SNR performances about AWGN and frequency flat Rayleigh fading channel related to the 64-QAM modulation is inspected in Figure 9, it can be seen that DWT-OFDM system provides high SNR improvement of approximately 8 dB for a BER value of 1E-3.

6 Conclusions

In this study, the performances of the DWT-OFDM system is comparatively analyzed and simulated with that of the conventional FFT-OFDM system via AWGN with AWGN and frequency flat Rayleigh fading channels for different modulation types. It has received considerable attention that the presented system provides high SNR improvement of approximately 6 dB for a BER value of 1E-5 in AWGN channel. Also, the obtained simulation results over AWGN and frequency flat Rayleigh fading channels have demonstrated that the presented DWT-OFDM system provides high SNR improvement of approximately 6 dB in 4-QAM, 5 dB in 16-QAM and 8 dB in 64-QAM modulation for a BER value of 1E-3. The performance improvement by the presented method is very significant with little increase on the complexity. The obtained simulation results approve that the presented technique can be used in future for wireless communications with high performance. In particular, when the spectrum efficiency and low level of received signal powers are issued in an embedded transceiver design, the DWT-OFDM system can easily be employed without sacrificing the performance.

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