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Comparative Analysis of Fast Fourier Transform and Discrete Wavelet Transform Based MIMO-OFDM

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Abstract – *The orthogonal frequency division multiplexing (OFDM) is used in mobile wireless communication systems including IEEE 802.16 (WiMAX), Long Term Evolution (LTE), Long Term Evolution Advanced (LTE-A), IEEE802.11x (Wi-Fi), Hiperlan/2, etc due to its high data rate capability, robustness against multi-path fading (particularly when combined with MIMO antenna technology), frequency selective fading, and its ability to leverage on the use of more bandwidth efficiently, without the problem of Inter Symbol Interference (ISI). Discrete Wavelet Transform (DWT) has strong advantages over Discrete Fourier Transform (DFT) which is a major technique in the achievement of the OFDM system. DWT allows time-frequency domain operation with flexibility and provides solutions to the various drawbacks identified in DFT based MIMO-OFDM technology including spectral wastage as a result of the inclusion of cyclic prefix and high Peak to Average Power Ratio (PAPR). This paper provides an overview of the basic principles of DFT and DWT based OFDM. DWT based OFDM in comparison with DFT based OFDM in MIMO-OFDM system was also investigated using MATLAB based simulations. The Authors has proposed a IDWT based OFDM in MIMO-OFDM systems as it outperforms the IDFT based MIMO-OFDM as shown by our simulation result where the Bit Error rate (BER) of DWT using 8QAM and QPSK modulation scheme is lower compared to the BER of DFT. Our results thus showed improved performance with the use of DWT over DFT in the MIMO-OFDM system.* ***Copyright © 2017 The Authors.***

Keywords*:* *Discrete Wavelet Transform (DWT), Discrete Fourier Transform (DFT), MIMO-OFDM, MATLAB, High Pass Filter, Low Pass Filter*

Nomenclature

OFDM	Orthogonal Frequency Division Multiplexing
WiMAX	IEEE802.16
LTE	Long Term Evolution
Wi-Fi	IEEE802.11
MIMO	Multiple Input Multiple Output
ISI	Inter-symbol Interference
DWT	Discrete wavelet Transform
DFT	Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IDFT	Inverse Discrete Fourier Transform
BPSK	Binary Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation

I. Introduction

Wireless communication system is faced with numerous challenges which include demand for higher network capacity, better quality of service, higher throughput, inadequate spectrum availability, fading and multipath distortion.

This therefore necessitates the need for new transmission techniques that will provide higher throughput, improved spectral efficiency and better quality of service (QoS). OFDM is one of the most useful technologies for enhancing data rate and throughput in the present and future wireless communication system since it has features for fighting ISI, channel fading and other wireless communication channel challenges [1]-[27]. The data bits to be transmitted are encoded in multiple sub-carriers using multicarrier modulation techniques called DFT, these are then sent simultaneously with each sub carrier modulated with modulation techniques such as BPSK, QPSK, 8QAM, and 16QAM etc. At the receiver, the different subcarriers are merged to produce a composite time-domain signal using the Fast Fourier Transform (FFT) operation [2].

DFT based OFDM, a key wireless broadband technology has combined efficiently with MIMO technology for enhanced spectrum efficiency utilization, higher data rate and higher throughput for users until recently when DWT (discrete wavelet transforms) was discovered. OFDM provides an efficient means to reduce the Inter Symbol Interference with the use of cyclic prefix (CP) but CP has the drawback of reducing the

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spectral containment of the channels. To overcome these drawbacks, DWT-OFDM is used as an alternative method. Cyclic prefix is not required in DWT-OFDM systems as wavelets possess orthonormal nature, thus satisfying the perfect reconstruction property and providing better spectral containment of the channels thus enhancing throughput [3]. In this paper, a comparative analysis of the bit error rate (BER) of both the IDFT based MIMO-OFDM and the IDWT based MIMO-OFDM systems using MATLAB Simulink was carried out.

This paper is organized as follows; Section 1 provides the Introduction. Section 2 explains multiple inputs and multiple output (MIMO) system. Section 3 gives an overview of the IDFT based OFDM while Section 4 gives an overview of the IDWT based OFDM. Section 5 is the review of related research while Section 6 is the result of the Simulations and subsequent conclusion

II. MIMO (Multiple Input Multiple Output)

The wireless communication system is faced with demand for spectrum availability and solutions to fading as well as multipath distortion. MIMO antenna technology present a technique for providing higher throughput, improve spectral efficiency and link reliability without increase in bandwidth and transmit power requirements. Basically, the major technique of MIMO are the Spatial Division Multiplexing, the Spatial Diversity (Transmit or Receive Diversity), related with this technique is the Space Time Block Coding which is sometimes referred to as Spatial Diversity and finally the Transmit Beam forming. There are three fundamental gains available by the use of the above techniques in a wireless network system, these include the multiplexing gain, the diversity gain and the antenna gain [4]. The combination of MIMO with OFDM modulation provides improvement in the BER performance of wireless communication systems hence increase in the data rate of system.

III. Basic Principles of FFT-OFDM

Single Carrier: for a signal with 10MHz bandwidth:

$$T = \frac{1}{B} = \frac{1}{10\text{MHz}} = (0.1)(10^{-s})\ \text{s} \tag{1}$$

$$T = 0.1\mu s \text{ (symbol time)}$$

Now the delay spread of wireless channel is given as:

$$T_d \approx 2\text{-}3\mu s \tag{2}$$

Therefore, symbol time $T << T_d$ the delay spread i.e. when delay time is larger than symbol time in wireless system, this lead to Inter Symbol Interference (ISI) in the system and degradation in the performance of the wireless network.

In providing solution to overcome ISI in broadband network, the larger bandwidth is split into sub-bands.

If there are N sub-bands, therefore, B of each sub-band $= B/N$:

$$\text{If } N\text{=1000, } B_{s/b} = (10)(10^6/1000) = 10 \text{ kHz}$$

Therefore, symbol time in each sub-band:

$$\text{T} = 1/B/N = N/B = 100/10\text{MHz} = 100\mu s \tag{3}$$

For T = 100μs compared to T_d of 2μ shows that the new symbol time is much greater than delay spread, thus solving the problem of ISI. Since symbol time is now greater than the network delay spread, for such a system with multiple sub-bands and multiple sub-carriers, the system is called Multi-Carrier Modulated (MCM) system.

If F_0 is the fundamental frequency = $\frac{B}{N}$ because the sub-carriers are placed at $-2F_0$, $-F_0$, 0, F_0, $2F_0$ and so on with a total of N sub-carriers.

Let the K^{th} sub-carrier be represented as:

$$KF_0 = K\left(\frac{B}{N}\right) \tag{4}$$

The transmitted signal on the K^{th} sub-carrier with symbol X_k is then given as:

$$x(t) = X_k e^{j2\pi kfot} \tag{5}$$

Net transmitted signal on all sub-carrier is given as:

$$T_x = \sum X_k e^{j2\pi kfot} \tag{6}$$

The received signal:

$$y(t) = \sum X_k e^{j2\pi kfot} \text{ (in the absence of noise)} \tag{7}$$

To extract X_L which is the symbol on L^{th} sub-carrier using Fourier series, X_L becomes:

$$X_L = f_0 \int_0^{1/f} e^{-j2\pi lfot}\, y(t)\, dt \tag{8}$$

where f_o is the fundamental frequency:

$$X_L = f_0 \int_0^{1/f} e^{-j2\pi lfot} \sum X_k\, e^{j2\pi kfot}\, dt \tag{9}$$

$$X_L = \sum X_k\, f_o \int_0^{1/f} e^{j2\pi(k-l)fot}\, dt \tag{10}$$

where $e^{j2\pi(k-l)fot}$ equal 0 if $k \neq L$ and equal 1 if $k = L$.

Thus equation (10) reduces to:

$$[X_L = \sum X_k\, \delta(k - L)] \tag{11}$$

where $\delta(k - L) = 1$ if $k = L$, $\delta(k - L) = 0$ if $k \neq L$.

Thus X_L symbol can be extracted which is done for all other sub-carriers at the receiver by correlating with $e^{j2\pi Lfot}$ (coherent demodulation) or matched filtering with $e^{-j2\pi lfot}(T - t)$ at the receiver.

III.1. IFFT Processing

Considering equation (6) where X_k is the symbol transmitted on the k[th] sub-carrier and $e^{j2\pi k f_o t}$ is the k[th] sub-carrier and kf_o is the k[th] sub carrier frequency. With number of sub-carriers N been very large in the order of a thousand, it means a thousand oscillator is needed to generate the thousand sub-carrier signals and each must be placed exactly at $-4f_o$, $-3f_o$, …….. f_o, $2f_o$ …… etc., otherwise it will be impossible to achieve orthogonality. However, since the signal is band limited, it can be sample at Nyquist rate of $2F_{max}$ to obtain:

$$2F_{max} = B/2 \times 2 = B \tag{12}$$

Thus sampling interval = $^1/_{\text{sampling freq}} = \frac{1}{B}$ therefore, $T = {}^1/_B$:

$$L^{\text{th}} \text{ sampling instant} = L\,T = {}^L/_B \tag{13}$$

From equation (6) the transmitter signal becomes:

$$\begin{aligned} x(t) = x(LT) &= \sum X_k e^{j2\pi kfoLT} = \\ &= \sum X_k e^{\frac{j2\pi kB}{N} L \frac{1}{B}} \\ x(L) &= \sum X_k e^{\frac{j2\pi kL}{N}} \end{aligned} \tag{14}$$

This is the expression for the IDFT or IFFT (IFFT is just a fast algorithm to evaluate IDFT).

Thus $x(L)$ is the L[th] IDFT points of X_o, X_1, X_2 X_{N-1} which is the different symbols transmitted on the N Sub-carriers over the wireless channel.

III.2. Cyclic Prefix

Considering a frequency selective channel which can be modeled as:

$$y(n) = h(o)\cdot x(n) + h(1)\cdot x(n\text{-}1) + \ldots + h(L\text{-}1)\cdot x(n\text{-}1+L) \tag{15}$$

The above channel thus has channels $h(0)$, $h(i)$, $h(2)$... …. $h(L\text{-}1)$ and symbols $x(n)$, $x(n\text{-}1)$, $x(n\text{-}2)$...$x(n\text{-}1+L)$ showing that this channel has Inter Symbol Interference leading to frequency selective fading. Transmitting two sets of sampled symbols over this channel consecutively and looking at the output of the channel, we have the output for $x(0)$ given as:

$$\begin{aligned} y(0) = h(0)\cdot x(0) + h(1)\cdot \tilde{x}(N\text{-}1) + h(2)\cdot \tilde{x}(N\text{-}2) + \ldots + \\ h(L - 1)\cdot \tilde{x}(N - L + 1) \end{aligned} \tag{16}$$

where $\tilde{x}$ and x are from the two sets of sampled symbols.

Thus there is an interference of the symbol from the other transmitted signal on the output of our signal of interest. That is, $h(1)\cdot\tilde{x}(N\text{-}1) + h(2)\cdot\tilde{x}(N\text{-}2) + \ldots + h(L - 1)\cdot\tilde{x}(N - L + 1)$ which are the interfering block of signals from the other signal called Inter Block Interference (IBI) which will be removed by the cyclic prefix.

This is done by taking L bar sample from the tail of the OFDM block and adding them in a cyclic fashion to the prefix or front of the OFDM block of the transmitted symbol. This process is known as cyclic prefix and is used to remove or avoid the ISI or IBI.

The addition of the cyclic prefix for mitigating against Inter Symbol Interference however reduces spectral efficiency and also increases the system complexity. Without the cyclic prefix, the OFDM based on IFFT has a lot of advantages with high spectral efficiency. The loss of this efficiency is caused by the inclusion of the cyclic prefix or guard interval, therefore a technique effecting OFDM without the inclusion of CP will restore this efficiency [5].

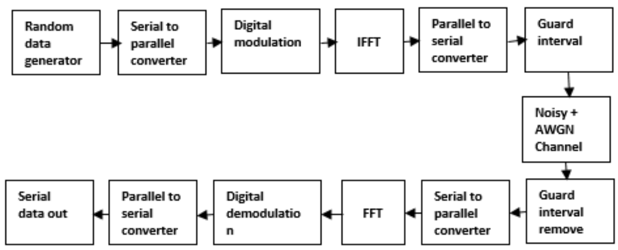

Fig. 1. FFT based OFDM transceiver block diagram

TABLE I
MIMO-OFDM SYSTEM SPECIFICATIONS

Parameter	Specification
Channel Model	Noisy Channel
Modulation	QPSK, 8QAM
Detector	ML Detector
Diversity Scheme	2×2
Separation Distance	1/2
Antenna Transmitting Power	Equally

IV. The Discrete Wavelet Transform

Suppose it is required to determine the frequency components of a signal at a certain time, a dirac delta pulse is used to cut out only this very short time window in the signal train and then transform it to the frequency domain. This time window can be shifted along the signal waveform such that for every position, the spectrum or frequency is calculated using Fourier Transform (FT). This process is repeated many times with a slightly shorter or longer window for every new cycle of the signal. The final result is a collection of time- frequency representation of the signal.

Mathematically, Wavelet Transform (WT) is given by:

$$Wf_{(s,u)} = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{s}} \psi(\frac{t-u}{s}) dt \quad (17)$$

The wavelet transform is designed to strike a balance between the frequency domain and the time domain by dilating and translating the mother wavelet so that very low frequency components at large *s* are seen while very high frequency component can be located precisely at small s [6]. This flexibility increases the time – frequency analysis.

The inverse wavelet transform is:

$$f(t) = \frac{1}{C_\psi} \int_0^{\infty} \int_{-\infty}^{\infty} Wf_{(s,u)} \frac{1}{\sqrt{s}} \psi(\frac{t-u}{s}) du \cdot ds/s^2 \quad (18)$$

$$C_\psi = \int_0^{\infty} \frac{|\psi(\omega)|^2}{\omega} d\omega < \infty \quad (19)$$

where C_ψ is the coefficient, The *s* parameter is inversely proportional to the frequency and is called the scaling factor and is greater than zero because negative scaling is undefined. *u* is the translation parameter indicating which region is of concern. With this transform (Equation (17)), one-dimensional signal *f*(*t*) can be mapped to a two dimensional coefficients $Wf_{(s,u)}$.

The two variables s and u can perform the time-frequency analysis; a particular frequency s can then be located at a particular time instance u. Note that, $\psi(\omega)$ in equation (19) is the Fourier transform of the mother wavelet $\psi(t)$ [6]. The wavelet transform is a new technology for splitting up data into different frequency components thus allowing for the study of each component separately.

IV.1. DWT Based MIMO-OFDM

The disadvantage of the Fourier expansion is that it has only frequency resolution and no time resolution meaning that it might be possible to determine all the frequencies present in a signal but may be difficult to know when they are present. The idea is to get a time-frequency joint representation of a signal by cutting the signal into several frequency parts and analyzing it at a certain moment in time, the wavelet transform is likely the most recent solution to overcome the shortcomings of the Fourier transform (FT) [7].

The main advantage of wavelet transform over Fourier transform is that it is discrete both in time as well as scale. DWT is used to remove the cyclic prefix thus decreasing the bandwidth wastage since the spectral containment of the channels in DWT-OFDM is better than FFT-OFDM. The transform is implemented by the use of filters. Low pass and high pass filters are employed to operate as Quadrature Mirror Filters (QMF) which satisfies perfect reconstruction and orthonormal properties. One filter of the analysis pair is a low pass filter (LPF), while the other one is a high pass filter (HPF). Each filter consists of a down-sampler to make the transform efficient. In DWT-OFDM, the input data is processed the same way as in FFT-OFDM but the advantage in this case is that the cyclic prefix is not required because of the overlapping nature of wavelet properties thus the essential modification in the conventional FFT-OFDM multicarrier scheme is the removal of the cyclic prefix blocks in the scheme [8].

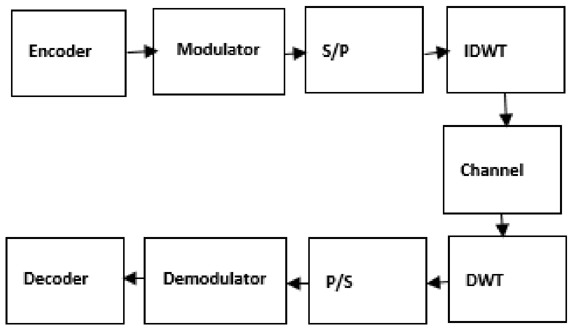

Fig. 2. IDWT based OFDM Transceiver block diagram

TABLE II
SIMULATIONS SETTINGS

SIMULATION PARAMETER	FFT-OFDM	DWT-OFDM
No of Data Carrier	96	96
No of Pilot Carrier	16	16
No of Guard carrier	44	44
Modulation Type	16QAM	16QAM
MIMO Order	Tx = 1, 2 Rx = 2	Tx = 1, 2 Rx = 2
Channel Type	AWGN, Rayleigh	AWGN, Rayleigh
Wavelet Used		Haat

V. Review of Related Research

The orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation scheme used in most state-of-the-art wireless communication networks like the IEEE802.11n, IEEE802.16e, the LTE/LTE-A [16], [18], [25], [26] and the recently released LTE-A Pro because of its advantage of spectral efficiency, immunity to multipath fading and its ability to combine effectively with MIMO system [9]. However, some of its disadvantages are the high PAPR and the inclusion of cyclic prefix which decreases its spectral efficiency [11], [13].

There has been several research works to provide solutions to the above OFDM problem including the use of other transform methods rather than the DFT/IDFT use in the present OFDM scheme. In [9], a combination of the Walsh Hadamard transforms (WHT) and the fast Hartley transform (FHT) into a new single orthonormal unitary transform is proposed in OFDM to reduce the high PAPR and achieve a better BER performance. In [12]-[14], [19], [20], a discrete wavelet transform (DWT) was proposed to show the superiority of DWT in terms of spectral efficiency and reduced PAPR. The merit of Discrete Wavelet Transform over other traditional transforms have led to tremendous focus on its application not only in OFDM according to [28] as DWT has proved very useful even in other application areas including its use in digital image watermarking scheme [10], where it combines with lifted wavelet transform (LWT) to produce less distortion rate with high reliability and less computation cost for watermarking purposes. In [15], state-of-the-art image or video compression techniques such as the JPEG2000 uses DWT for transmission over OFDM channels that produces an energy saving approach to image and video compression data transmission. [22], [24] did a series of BER comparison for FFT-OFDM and DWT-OFDM using various modulation schemes from 16QAM up to 128QAM, 64-PSK, 128-PSK with Haar, Biorthogonal, reverse Biorthogonal etc wavelets and showed that DWT-OFDM outperform FFT-OFDM in all cases under consideration, in the case of [17], DWT-OFDM is used in channel estimation algorithm where least square (LS) and linear minimum mean square error (LMMSE) algorithms were used in DWT-OFDM system as compared to FFT-OFDM system and showed that both LS and LMMSE performed better in DWT-OFDM based system than in FFT-OFDM system for channel estimation purposes.

By considering all the above discussed approaches, we proposed a novel model which considered the effect of DWT on hybrid MIMO-OFDM as opposed to many which considered OFDM alone, we used a 2×2 MIMO model with Alamouti code.

VI. Simulation Results

By means of the MATLAB simulation (Fig. 3 and Fig. 4), the performance of the IFFT and IDWT based MIMO-OFDM system is analyzed by bit error rate versus signal to noise ratio with the results shown in Fig. 5 to Fig. 7.

The BER performance using 8QAM as the modulation scheme shown in Fig. 5, is seen to give a signal to noise ratio of between 0 to 25dB with respect to DWT with the FFT version showing higher bit error rates. As the signal to noise ratio increases to 70dB, the DWT MIMO-OFDM system is seen to outperform the FFT MIMO-OFDM system. Comparing the BER performance using QPSK modulation scheme, the DWT MIMO-OFDM system records minimum BER in comparison with its FFT counterpart thereby justifying the improved performance of the MIMO-OFDM system using Discrete Wavelet Transform.

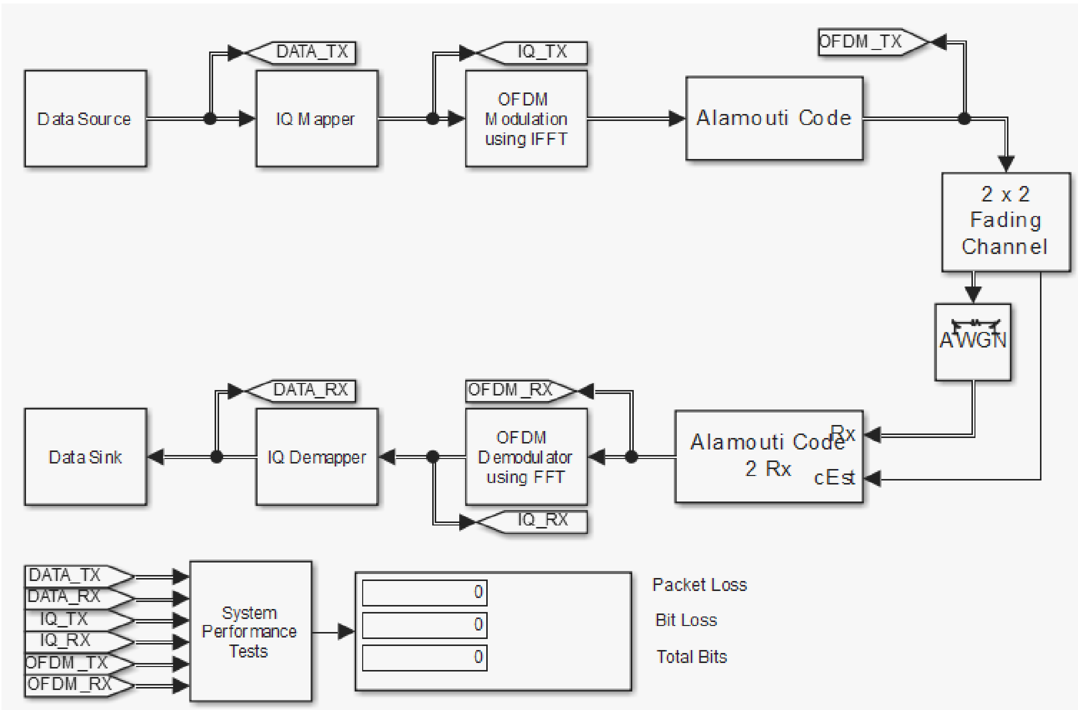

Fig. 3. IFFT based MIMO-OFDM Simulation

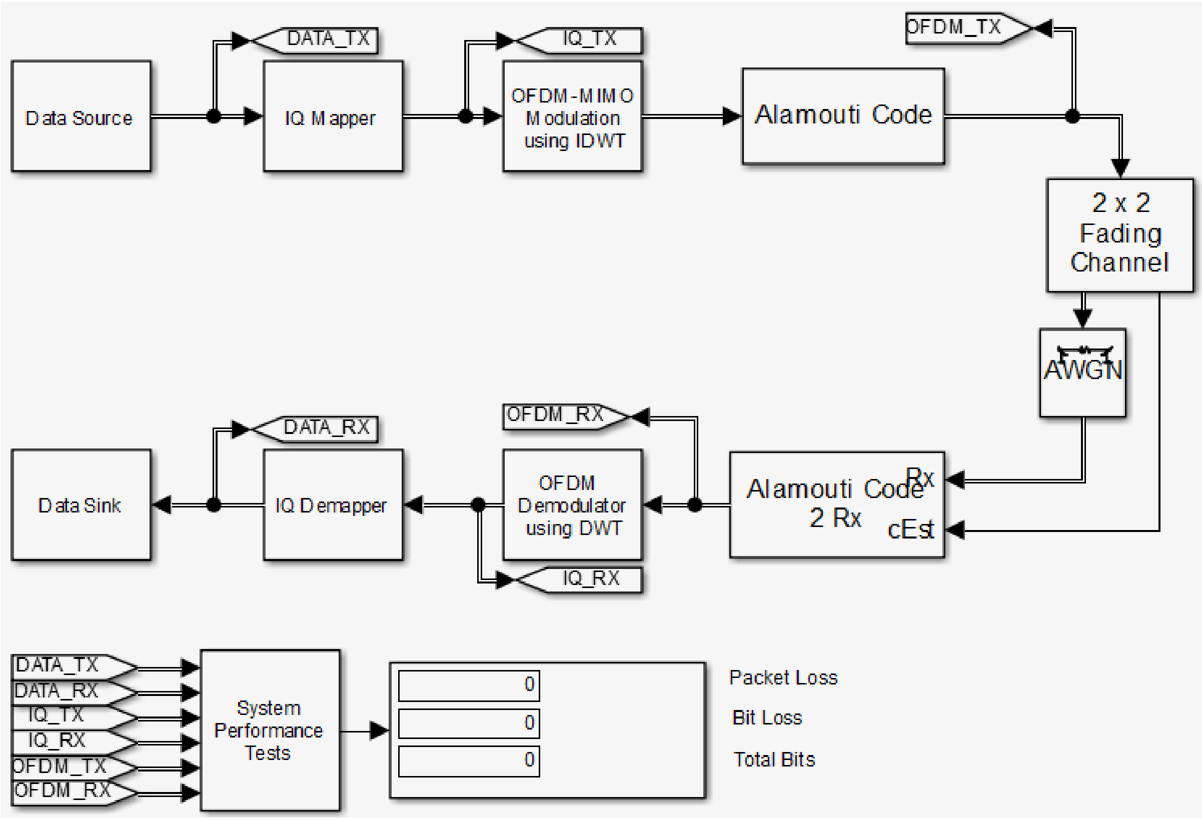

Fig. 4. IDWT based MIMO-OFDM Simulation

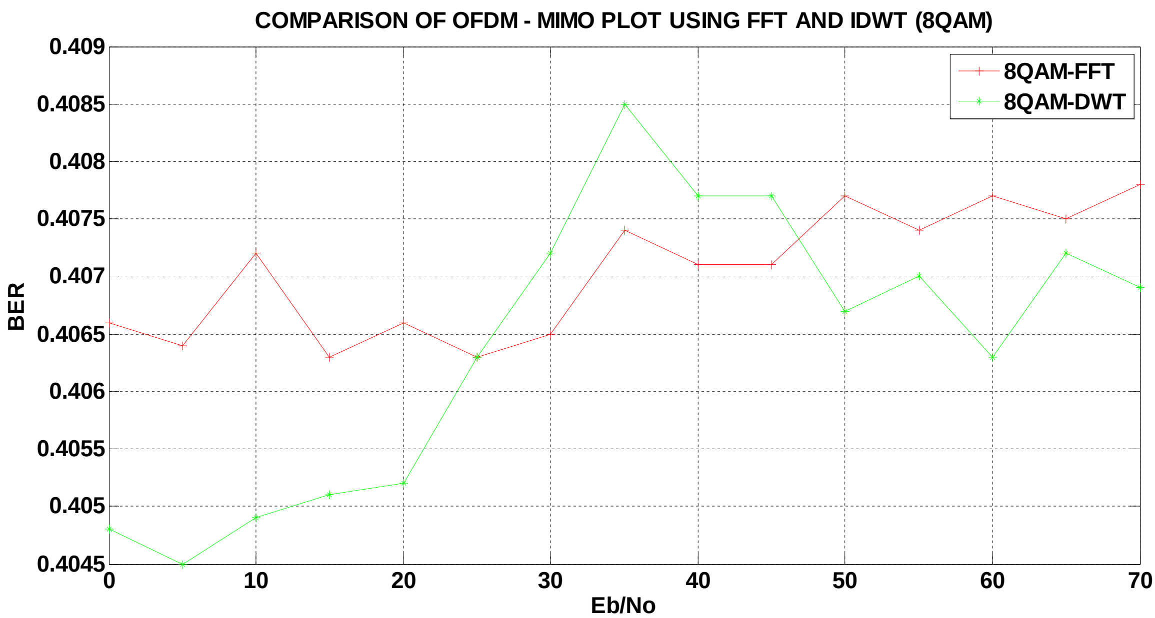

Fig. 5. Comparison of OFDM-MIMO using IFFT & IDWT using 8QAM modulation

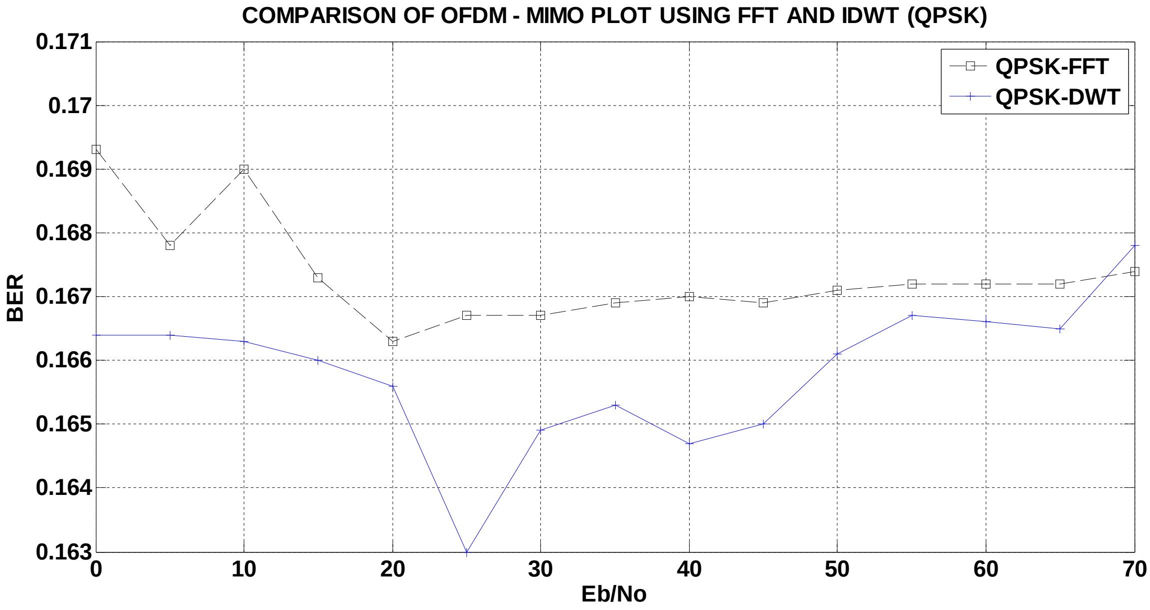

Fig. 6. Comparison of OFDM-MIMO using IFFT & IDWT using QPSK modulation

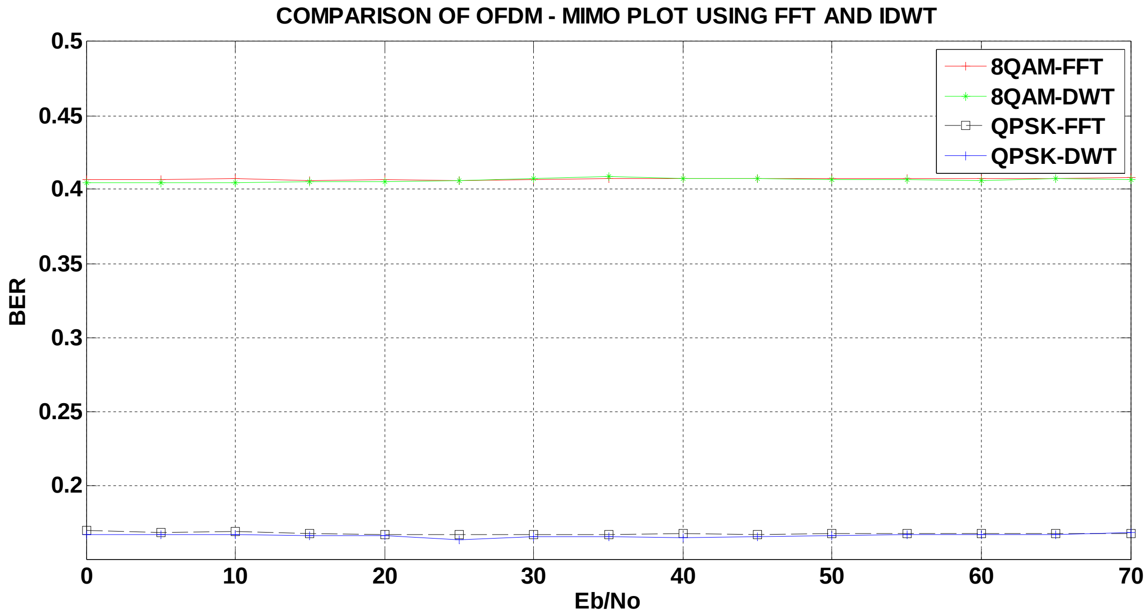

Fig. 7. Comparison of OFDM-MIMO using IFFT & IDWT

VII. Conclusion

This paper has investigated the performance of MIMO-OFDM system using IFFT and IDWT. The algorithm used to improve the performance of the system utilizes IDWT which eliminates the use of cyclic prefix thereby maximizing the bandwidth requirement while minimizing the bit error rate of the system. With due consideration of a noisy channel typical of Rayleigh channel with multipath and sometimes direct line of sight, the overall system performance of spectral efficiency, throughput enhancement and seamless broadband communication system can be achieved with the use of discrete wavelet transform in the MIMO-OFDM system.

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