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The performance of multiwavelets based OFDM system under different channel conditions

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ABSTRACT

In wireless communication reception, the reliability of orthogonal frequency division multiplexing (OFDM) is limited because of the time-varying nature of the channel. This causes inter-carrier interference (ICI) and increases inaccuracies in channel tracking. This can effectively be avoided at the cost of power loss and bandwidth expansion by inserting a cyclic prefix guard interval before each block of parallel data symbols. However, this guard interval decreases the spectral efficiency of the OFDM system as the corresponding amount. Recently, it was found that based on Haar-orthonormal wavelets, discrete wavelet-based OFDM (DWT-OFDM) is capable of reducing the inter symbol interference (ISI) and ICI, which are caused by the loss in orthogonality between the carriers. DWT-OFDM can also support much higher spectrum efficiency than discrete Fourier-based OFDM (DFT-OFDM). In this paper the DFT-OFDM is replaced by Multiwavelets OFDM (DMWT-OFDM) in order to further reduce the level of interference and increase spectral efficiency. It is found that proposed Multiwavelet design achieves much lower bit error rates, increases signal to noise power ratio (SNR), and can be used as an alternative to the conventional OFDM. The proposed OFDM system was modeled tested, and its performance was found under different channel conditions.

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1. Introduction

OFDM system is one of the most promising technologies for current and future wireless communications [1]. It is a form of multi-carrier modulation (MCM) technologies [2–4] where data bits are encoded to multiple sub-carriers, while being sent simultaneously. The process of combining different sub-carriers to form a composite time-domain signal is achieved using Fast Fourier transform (FFT) and inverse FFT (IFFT) operations [5,6].

The main problem in the design of a communications system over a wireless link is to deal with multi-path fading, which causes a significant degradation in terms of both the reliability of the link and the data rate [7]. Multi-path fading channels have a severe effect on the performance of wireless communication systems even those systems that exhibits efficient bandwidth, like OFDM [8]. There is always a need for developments in the realization of these systems as well as efficient channel estimation and equalization methods to enable these systems to reach their maximum performance [9,10]. The OFDM receiver structure allows relatively straightforward signal processing to combat channel delay spreads, which was a prime motivation to use OFDM modulation methods in several standards [11–22].

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In transmissions over a radio channel, the orthogonality of the signals is maintained only if the channel is flat and time-invariant, channels with a Doppler spread and the corresponding time variations corrupt the orthogonality of the OFDM sub-carrier waveforms [23]. In a dispersive channel, self-interference occurs among successive symbols at the same sub-carrier casing ISI, as well as among signals at different sub-carriers casing ICI. For a time-invariant but frequency-selective channel, ICI, as well as ISI, can effectively be avoided by inserting a cyclic prefix before each block of parallel data symbols at the cost of power loss and bandwidth expansion [5,24].

Some solutions for ICI mitigation, such as pre-coding for self-cancellation [25], require a modification of the transmit format so that these are not suitable for existing standards [26]. Other techniques may not be suitable for high vehicle speeds or become too complex for consumer products. A method to reduce the ISI is to increase the number of sub-carriers by reducing the bandwidth of each sub-channel while keeping the total bandwidth constant [27]. Hirosaki [28] suggested an equalization algorithm in order to suppress both ISI and ICI caused by the channel impulse response or timing and frequency errors. The narrowband nature of sub-carriers makes the signal robust against frequency selectivity, however OFDM is relatively sensitive to time selectivity, which is due to rapid time variations of a mobile channel. Time variations corrupt the orthogonality of the OFDM sub-carrier waveforms so that ICI occurs [29].

Conventional OFDM/QAM systems are robust for multi-path channels due to the cyclically prefixed guard interval which is inserted between consequent symbols to cancel ISI. However, this guard interval decreases the spectral efficiency of the OFDM system as the corresponding amount [30]. Thus, there have been approaches of wavelet-based OFDM which does not require the use of the guard interval [31–35]. This alternate has better spectral efficiency than the conventional OFDM/QAM system. Wavelet bases have been introduced into the communication field as an alternative approach to Multi-carrier modulation (MCM) [36–45]. In [36], Lindsey discusses the possibility of applying multidimensional signals to orthogonally multiplexed communications. The ISI/ICI of MCM schemes with wavelet base and Fourier base is compared in [39]. Reference [42] presents a DWT-OFDM that can support much higher spectrum efficiency than DFT-OFDM. Reference [46] investigates the bit error rate (BER) performance of MCM systems with different orthogonal bases and shows that they have advantages under specified channel conditions. It is found that OFDM based on Haar orthonormal wavelets (DWT-OFDM) are capable of reducing the ISI and ICI, which are caused by the loss in orthogonality between the carriers, Haar wavelet is employed due to its simplicity.

In this paper further performance gains were made by looking at alternative orthogonal bases functions and finding a better transform rather than Fourier and wavelet transform it is a Discrete Multiwavelets transform (DMWT). Multiwavelets are very similar to wavelets but have some important differences. Wavelets may be described in the context of a multi-resolution analysis. In fact, it is possible to have more than one scaling (and wavelet) function. This is the idea behind Multiwavelets, which are a natural expansion of the wavelets. Multiwavelets are designed to be simultaneously symmetric, orthogonal and having short supports with high approximation power, which cannot be achieved at the same time for wavelet using only one scaling function. The trick is to increase the number of scaling functions to raise the approximation power rather than one scaling function. A new proposed OFDM system will be introduced based on a fast computation method for DMWT, it is DMWT-OFDM. The purpose of this multiplicity is to achieve more properties which can not be combined in other transforms (Fourier and wavelet) [47].

2. A proposed fast computational method for DMWT and inverse DMWT of 1D signals

A newer alternative to the wavelet transform is the multiwavelet transform. Multiwavelets are very similar to wavelets but have some important differences. In particular, whereas wavelets have an associated scaling function $\phi(t)$ and wavelet function $\psi(t)$, multiwavelets have two or more scaling and wavelet functions. For notational convenience, the set of scaling functions can be written using the vector notation $\Phi(t) = [\,\phi_1(t) \quad \phi_2(t) \quad \dots \quad \phi_r(t)\,]^T$, where $\Phi(t)$ is called the multiscaling function. Likewise, the multiwavelet function is defined from the set of wavelet functions as $\Psi(t) = [\,\psi_1(t) \quad \psi_2(t) \quad \dots \quad \psi_r(t)\,]^T$. When $r = 1$, $\Psi(t)$ is called a scalar wavelet, or simply wavelet. While in principle n can be arbitrarily large, the multiwavelets studied to date are primarily for $r = 2$.

The multiwavelet two-scale equations resemble those for scalar wavelets [48]:

$$\Phi(t) = \sqrt{2} \sum_{k=-\infty}^{\infty} H_k \Phi(2t-k), \tag{1}$$

$$\Psi(t) = \sqrt{2} \sum_{k=-\infty}^{\infty} G_k \Phi(2t-k). \tag{2}$$

However, that H_k and G_k are *matrix* filters, i.e. H_k and G_k are $n \times n$ matrices instead of scalars. The matrix elements in these filters provide more degrees of freedom than a traditional scalar wavelet. These extra degrees of freedom can be used to incorporate useful properties into the multiwavelet filters, such as orthogonality, symmetry, and high order of approximation. The key, then, is to figure out how to make the best use of these extra degrees of freedom. Multifilter construction methods are already being developed to exploit them. However, the multi-channel nature of multiwavelets also means that the sub-band structure resulting from passing a signal through a multifilter bank is different. Sufficiently

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different, in fact, so that established quantization methods do not perform as well with multiwavelets as they do with wavelets [49].

A very important multiwavelet filter is the GHM filter proposed by Geronimo, Hardian, and Massopust [50]. The GHM basis offers a combination of orthogonality, symmetry, and compact support, which cannot be achieved by any scalar wavelet basis [51]. There are four remarkable properties of the GHM scaling functions [52]:

- They each have short support (the intervals [0; 1] and [0; 2]).
- Both scaling functions are symmetric, and the wavelets form a symmetric/antisymmetric pair.
- All integer translates of the scaling functions are orthogonal.
- The system has second order of approximation.

For GHM system H_k are four scaling matrices H_0, H_1, H_2, and H_3 [52]:

$$H_0 = \begin{bmatrix} \frac{3}{5\sqrt{2}} & \frac{4}{5} \\ -\frac{1}{20} & -\frac{3}{10\sqrt{2}} \end{bmatrix}, \qquad H_1 = \begin{bmatrix} \frac{3}{5\sqrt{2}} & 0 \\ \frac{9}{20} & \frac{1}{\sqrt{2}} \end{bmatrix},$$
$$H_2 = \begin{bmatrix} 0 & 0 \\ \frac{9}{20} & -\frac{3}{10\sqrt{2}} \end{bmatrix}, \qquad H_3 = \begin{bmatrix} 0 & 0 \\ -\frac{1}{20} & 0 \end{bmatrix} \tag{3}$$

also, G_k for GHM system are four wavelet matrices G_0, G_1, G_2, and G_3:

$$G_0 = \begin{bmatrix} -\frac{1}{20} & -\frac{3}{10\sqrt{2}} \\ \frac{1}{10\sqrt{2}} & \frac{3}{10} \end{bmatrix}, \qquad G_1 = \begin{bmatrix} \frac{9}{20} & -\frac{1}{\sqrt{2}} \\ -\frac{9}{10\sqrt{2}} & 0 \end{bmatrix},$$
$$G_2 = \begin{bmatrix} \frac{9}{20} & -\frac{3}{10\sqrt{2}} \\ \frac{9}{10\sqrt{2}} & -\frac{3}{10} \end{bmatrix}, \qquad G_3 = \begin{bmatrix} -\frac{1}{20} & 0 \\ -\frac{1}{10\sqrt{2}} & 0 \end{bmatrix}. \tag{4}$$

The low pass filter H_k and high pass filter G_k consist of coefficients corresponding to the dilation equation (1) and wavelet equation (2). However in the multiwavelet setting these coefficients are n by n matrices, and during the convolution step they must multiply vectors (instead of scalars). This means that multifilter banks need n input rows. The most obvious way to get input rows from a given signal is to repeat the signal. Two identical rows go into the multifilter bank. This procedure is called “Repeated row” which introduces oversampling of the data by a factor of two. In the one-dimensional signals the “repeated row” scheme is convenient and powerful to implement [52,53].

2.1. Fast computation of DMWT for 1D signals

By using an over-sampled scheme of preprocessing (repeated row), the DMWT matrix is doubled in dimension compared with that of the input, which should be a square matrix $N \times N$ where N must be power of two. Transformation matrix dimensions are equal to input signal dimension after preprocessing. To compute a single-level 1D discrete Multiwavelet transform, the following algorithm should be followed [54]:

1. Checking input dimensions: Input vector should be of length N, where N must be power of two.
2. Constructing a $2N \times 2N$ transformation matrix: Using GHM low-pass and high-pass filters matrices given in (3) and (4), the transformation matrix can be written as follows:

$$W = \begin{bmatrix} H_0 & H_1 & H_2 & H_3 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & H_0 & H_1 & H_2 & H_3 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ldots & \vdots & \vdots & \vdots & \vdots \\ H_2 & H_3 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & H_0 & H_1 \\ G_0 & G_1 & G_2 & G_3 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & G_0 & G_1 & G_2 & G_3 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ldots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & G_0 & G_1 & G_2 & G_3 \\ G_2 & G_3 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & G_0 & G_1 \end{bmatrix}. \tag{5}$$

Preprocessing the input signal by repeating the input stream with the same stream multiplied by a constant α. For GHM system functions $\alpha = 1/\sqrt{2}$ [52].

3. Transformations of input vector which can be done by apply matrix multiplication to the $2N \times 2N$ constructed transformation matrix by the $2N \times 1$ preprocessing input vector.

Finally, a $2N \times 1$ DMWT matrix results from the $N \times 1$ original matrix using repeated row. A general example for computing 1D DMWT using an oversampled scheme of preprocessing involves the following steps:

1. Let 4-component vector be the input 1D signal,

$$X = [\, x_0 \quad x_1 \quad x_2 \quad x_3 \,],$$
$$X = [\, 5 \quad 16 \quad 3 \quad 7 \,].$$

2. For an 4×1 input 1D signal X, construct a 4×4 transformation matrix, W, using GHM low and high pass filters matrices given in (3) and (4). As GHM filters H's and G's are 2×2 matrices, the transformation matrix W dimension after substituting filters coefficients value will be 8×8 matrix which has the same dimension of the input matrix after repeated-row preprocessing:

$$W = \begin{bmatrix} \frac{3}{5\sqrt{2}} & \frac{4}{5} & \frac{3}{5\sqrt{2}} & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{20} & -\frac{3}{10\sqrt{2}} & \frac{9}{20} & \frac{1}{\sqrt{2}} & \frac{9}{20} & -\frac{3}{10\sqrt{2}} & -\frac{1}{20} & 0 \\ 0 & 0 & 0 & 0 & \frac{3}{5\sqrt{2}} & \frac{4}{5} & \frac{3}{5\sqrt{2}} & 0 \\ \frac{9}{20} & -\frac{3}{10\sqrt{2}} & -\frac{1}{20} & 0 & -\frac{1}{20} & -\frac{3}{10\sqrt{2}} & \frac{9}{20} & \frac{1}{\sqrt{2}} \\ -\frac{1}{20} & -\frac{3}{10\sqrt{2}} & \frac{9}{20} & -\frac{1}{\sqrt{2}} & \frac{9}{20} & -\frac{3}{10\sqrt{2}} & -\frac{1}{20} & 0 \\ \frac{1}{10\sqrt{2}} & \frac{3}{10} & -\frac{9}{10\sqrt{2}} & 0 & \frac{9}{10\sqrt{2}} & -\frac{3}{10} & -\frac{1}{10\sqrt{2}} & 0 \\ \frac{9}{20} & -\frac{3}{10\sqrt{2}} & -\frac{1}{20} & 0 & -\frac{1}{20} & -\frac{3}{10\sqrt{2}} & \frac{9}{20} & -\frac{1}{\sqrt{2}} \\ \frac{9}{10\sqrt{2}} & -\frac{3}{10} & -\frac{1}{10\sqrt{2}} & 0 & \frac{1}{10\sqrt{2}} & \frac{3}{10} & -\frac{9}{10\sqrt{2}} & 0 \end{bmatrix}.$$

3. Apply repeated row preprocessing to the input X, which results in P matrix,

$$P = [\, x_0 \quad \alpha x_0 \quad x_1 \quad \alpha x_1 \quad x_2 \quad \alpha x_2 \quad x_3 \quad \alpha x_3 \,],$$
$$P = [\, 5 \quad 3.5355 \quad 16 \quad 11.3137 \quad 3 \quad 2.1213 \quad 7 \quad 4.9497 \,].$$

4. Transformation of input vector which can be done as follows: $[Z] = [W] \times [P]^T$,

$$Z = [\, z_0 \quad z_1 \quad z_2 \quad z_3 \quad z_4 \quad z_5 \quad z_6 \quad z_7 \,],$$
$$Z = [\, 11.738 \quad 14.75 \quad 5.9397 \quad 6.75 \quad -1.25 \quad -7.9903 \quad -0.25 \quad -2.6163 \,].$$

2.2. *Fast computation of inverse DMWT for 1D signals*

To reconstruct the original signal from the discrete multiwavelets transformed signal, the inverse discrete Multiwavelets transform (IDMWT) should be used. Reconstruction matrix which is the inverse (or transpose) of the transformation matrix (5) can be used for computing IDMWT. An oversampled scheme of post-processing should be used in computing IDMWT [54]. To compute a single level 1D Inverse discrete multiwavelets transform using over-sampled scheme of post-processing, the following algorithm should be followed:

1. Apply shuffling by arranging the row pairs 1, 2, and $3, 4, \dots, N-1, N$ of the $2N \times 1$ matrix to be the row pairs 1, 2 and $5, 6, \dots, 2N-1, 2N-2$ of the resulting matrix and arranging the row pairs $N+1$, $N+2$ and $N+3, N+4, \dots, 2N-1, 2N$ of the $2N \times 1$ matrix to be the row pairs 3, 4, and $7, 8, \dots, 2N-1, 2N$ of the resulting matrix.
2. Multiply a $2N \times 2N$ reconstruction matrix ($2N \times 2N$ transformation matrix (5) transpose) with the resulting $2N \times 1$ shuffled matrix.
3. Apply post-processing by discarding the even rows $2, 4, \dots, 2N$ from the row reconstructed $2N \times 1$ matrix to have an $N \times 1$ original reconstructed 1D signal matrix.

3. Proposed system for DMWT-OFDM

In the previous section, a new DMWT computation method was proposed that verify the potential benefits of multiwavelets and gains much improvement in terms of low computational complexity. The verification of the new developed methods using computational aspects was also developed. Below are provided some concluding notes obtained on the proposed algorithms:

- A single level decomposition in the multiwavelet domain is equivalent to two scalar wavelet decompositions. Thus although computation complexity is double for DMWT compared to DWT, the levels of computation are less by half to get the same signal (image) quality.

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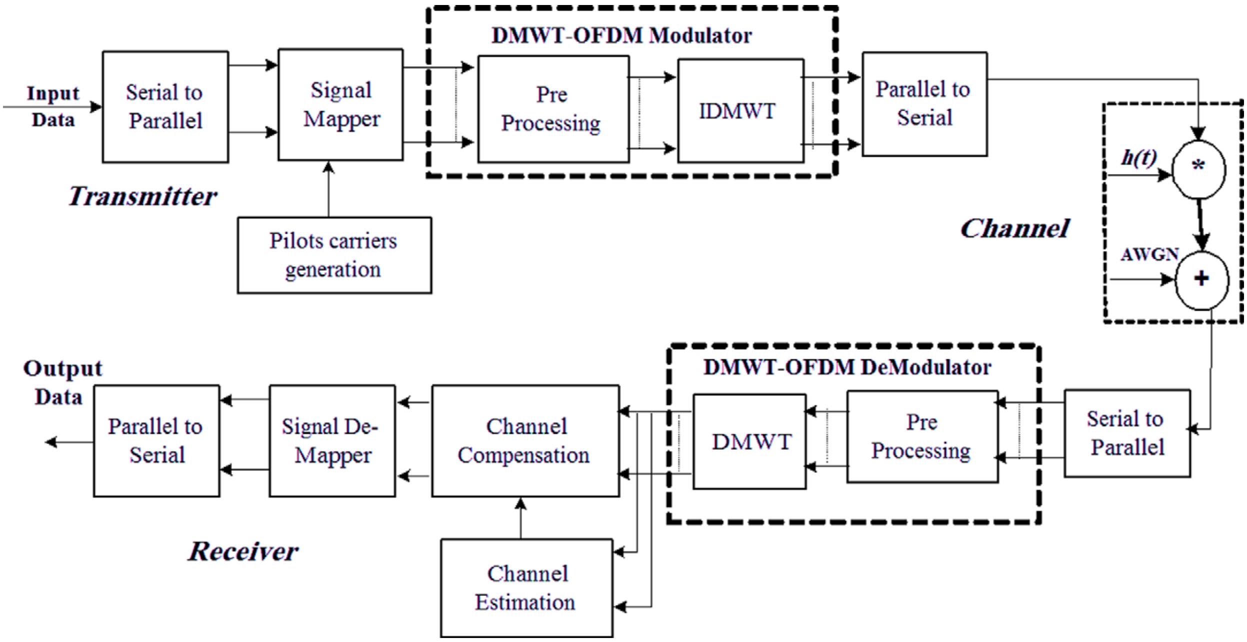

Fig. 1. Block diagram of DMWT-OFDM system.

- Multiwavelets filter banks require a vector-valued input signal. This is another issue which is addressed when Multiwavelets are used in the transform process. A scalar-valued input signal must some how be converted into a suitable vector-valued signal. This conversion is called preprocessing.
- The most obvious way to get two input rows from a given signal is to repeat the signal using repeated row preprocessing (over-sampled scheme).
- Using repeated row preprocessing introduces an oversampling of data by a factor of two, which doubles the original signal (image) dimensions. At the same time, the upper left-most sub-band of the decomposed image has half dimensions of the original.
- The proposed method has two promising features: it can support a low-resolution transmission from the original stream, and the ability to adapt the quality to the required bit rate. These features are also desirable for internet transmission at very low bit rates.
- The waveforms of the GHM Multiwavelets for the first decomposition $D = 1$ has $r = 2$ and support length of $L = 3$. According to multiwavelet theory a given bandwidth can be divided into $r \times 2^D$ orthogonal sub-bands with a decomposition level D.
- The support length $L = 3$ means that the symbol overlapping can be extend to 3 times. Hence the ratio of the FFT-OFDM and DMWT-OFDM sub-carries is $[N : (n + 2)/3]$ is equal to 3. This will result in increasing the overlapping of the sub-carriers in the time domain and this intern improves the band efficiency.
- It can be seen that the interference decreases sharply with the growing length of the filter for the DWMT-OFDM in comparison with that of conventional FFT-OFDM.
- According to the analyses of FFT-OFDM the transmitted signal is given by

$$f_F(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} n_k e^{j2\pi kt/T}, \quad 0 \leqslant t \leqslant T,$$

where n_k are the data, N is the number of sub carriers, and T is the data duration.

In order to replace the FFT in OFDM with DMWT the transmitted signal can be expressed as

$$f_W(t) = \frac{1}{\sqrt{2^D r}} \sum_{d=0}^{2^D-1} \sum_{i=1}^{r} n_{d,i} \Phi_{d,i}(t), \quad 0 \leqslant t \leqslant T.$$

As a result the average normalized ISI and ICI power will decrease with the increasing of sub-carriers.

The block diagram of the proposed system for OFDM is depicted in Fig. 1. It is very similar to that of DWT-OFDM. The processes of serial to parallel (S/P) converter, signal demapper, and insertion of training sequence are the same as in the DWT-OFDM system. The DMWT-based OFDM modulator consists of pre-processing block and IDMWT processing block and the DMWT-based OFDM demodulator consists of pre-processing block and IDMWT processing block as shown in Fig. 1.

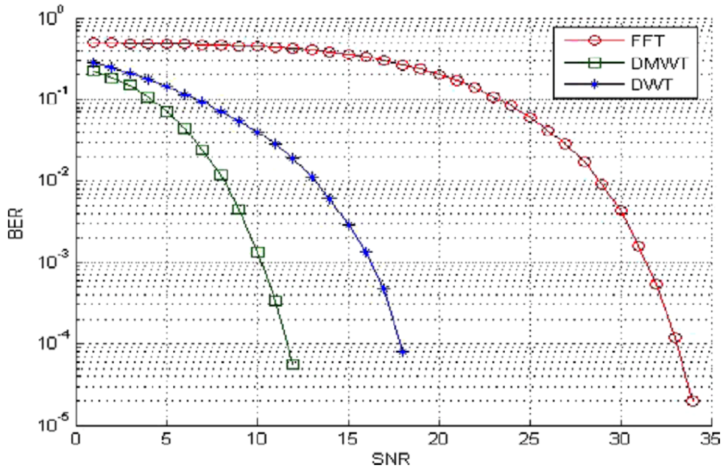

Fig. 2. BER performance of DMWT-OFDM in AWGN channel model.

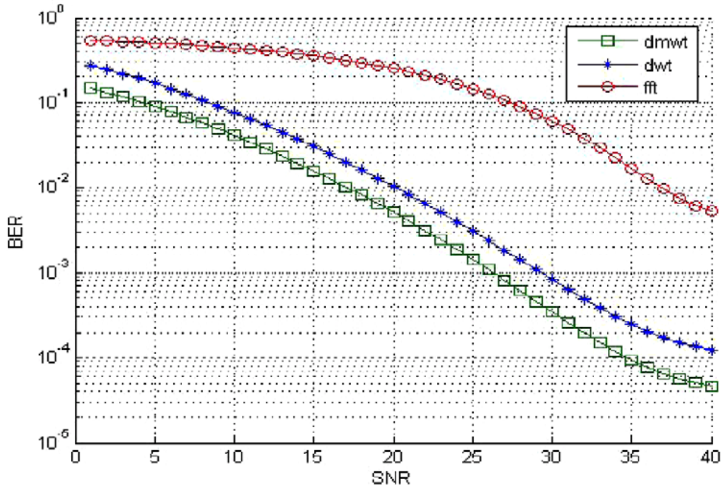

Fig. 3. The BER performance of DMWT-OFDM in FFC at max. Doppler shift = 5 Hz.

After a computation of IDMWT for 1D signal using an over-sampled scheme of preprocessing (repeated row), the IDMWT matrix is doubled in dimension compared with that of the input, which should be a square matrix $N \times N$. Hence the DMWT-OFDM will have half the FFT-OFDM bandwidth. Transformation matrix dimensions equal input signal dimensions after preprocessing.

4. Results and discussion of the proposed systems

In this section the simulations of the proposed DMWT-OFDM system are provided using MATLAB version 7. The bit error rate (BER) performance of the OFDM system is simulated for different channel models: additive white Gaussian noise (AWGN) channel, flat fading channel (FFC), and selective fading channel. In this simulation, the modulation type used is BPSK, number of sub-carriers are 64 and, the bandwidth used was 5 MHz. All simulation results are provided as a function of signal-to-noise-ratio (SNR) defined as the ratio of signal power to noise power and usually expressed with dB: SNR (in dB) $= 10\log(S/N)$; where S is the signal power and N is the noise power.

4.1. Performance of DMWT-OFDM in AWGN channel

Fig. 2 shows the results of simulation for BER performance of DMWT-OFDM in AWGN channel. It is clearly seen that DMWT-OFDM has much better performance than the other two systems, FFT-OFDM and DWT-OFDM. For example to have $BER = 10^{-3}$ DMWT-OFDM requires 10 dB SNR, while DWT-OFDM requires 16.5 dB and FFT-OFDM requires 31.5 dB SNR. This reflects the fact that the orthogonality of the DMWT-OFDM sub-carrier waveforms is much better than that for the other types, FFT-OFDM and DWT-OFDM.

The efficiency of DMWT-OFDM increases with decreasing the required value of BER.

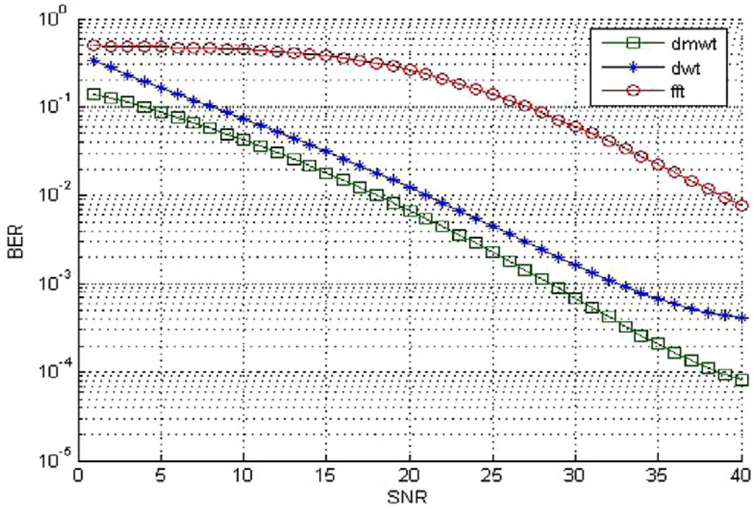

Fig. 4. The BER performance of DMWT-OFDM in FFC at max. Doppler shift = 500 Hz.

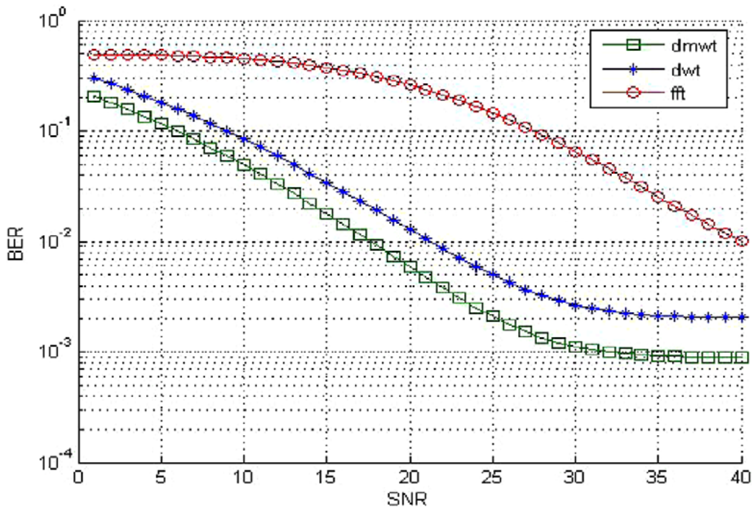

Fig. 5. The BER performance of DMWT-OFDM in FFC at max. Doppler shift = 1100 Hz.

4.2. Performance of DMWT-OFDM in FFC

In this channel, in addition to AWGN all frequency components of signal will be affected by a constant attenuation and a linear phase distortion, which has been chosen to have a Rayleigh distribution. Fig. 3 shows BER performance of DMWT-OFDM in FFC at maximum Doppler shift equal 5 Hz. From Fig. 3 it is seen that to have $BER = 10^{-4}$ the required SNR for DMWT is about 34 dB, while for DWT-OFDM it is about 40 dB and for FFT-OFDM it is required 40 dB of SNR to have BER about $BER \approx 5 \times 10^{-3}$. So DMWT-OFDM has about 6 dB gain improvement over DWT at $BER = 10^{-4}$. And in general DMWT-OFDM significantly increases SNR improvement and has a big advantage over the other two systems for this channel model.

Other Doppler shifts are used for simulations in FFC, and the BER performance of DMWT-OFDM, DWT-OFDM, and FFT-OFDM in FFC at maximum Doppler shifts values equal 500 Hz, and 1100 Hz is found. Fig. 4 provides BER performance of the three types of OFDM at maximum Doppler shift value equal 500 Hz and Fig. 5 depicts BER performance of the three types of OFDM at maximum Doppler shift value equal 1100 Hz. For the three cases of Doppler shift, DMWT-OFDM has better performance than the two others.

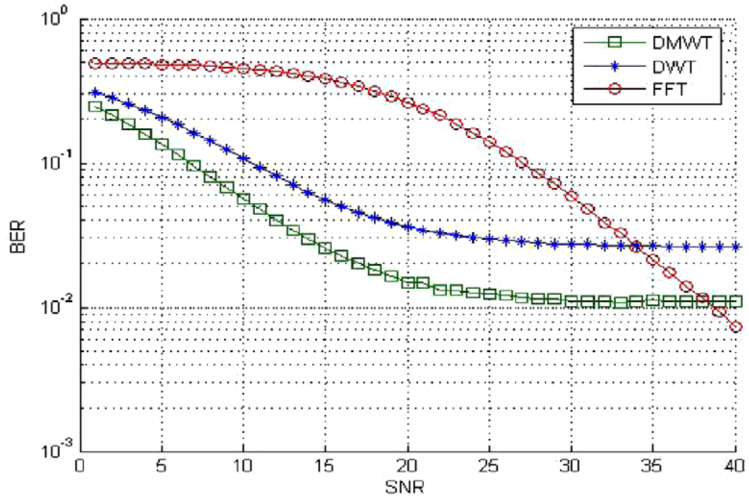

Fig. 6. The BER performance of DMWT-OFDM in selective fading channel at max Doppler shift = 5 Hz.

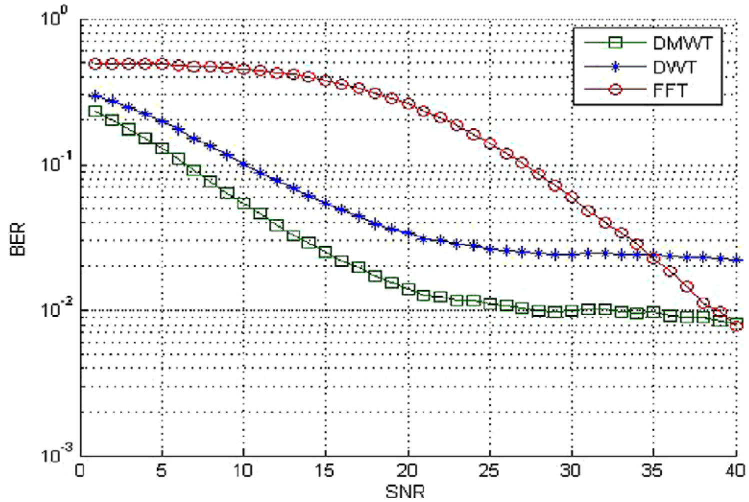

Fig. 7. The BER performance of DMWT-OFDM in selective fading channel at max Doppler shift = 500 Hz.

4.3. BER performance of DMWT-OFDM in selective fading channel

In this section, the channel model is selected to be selective fading channel, where the parameters of the second ray channel is assumed with a second path gain of −10 dB, and second path delay of one sample. Fig. 6 clearly shows that BER performance of DMWT-OFDM in this case is also better than DWT-OFDM and FFT-OFDM. DMWT-OFDM has BER performance equal 10^{-2} at $SNR = 30$ dB and the FFT-OFDM has the same BER performance at 39 dB. BER performance of DWT-OFDM becomes constant after a certain SNR. For this case it was constant and equal 3×10^{-2} after $SNR = 25$ dB. From these results it can be concluded that DMWT-OFDM has best performance than the other two systems DWT-based and FFT-based in the different channels that have been studied.

The three systems are simulated and tested for 500 Hz and 1100 Hz maximum Doppler shift. The results of BER performance for the two cases are given in Figs. 7 and 8. From simulation results it can be concluded that DMWT-OFDM has best performance than the other two systems: DWT-based and FFT-based.

Now different values of second path gain are used to study the effect of second path gain on BER performance of the three systems. Depending on results provided in Figs. 9 and 10 for gains −1 dB and −20 dB respectively, and for maximum Doppler shift = 5 Hz, Multiwavelet based OFDM still has better performance than the two other designs.

The behavior of BER performance of DMWT-OFDM in selective fading channel is similar to that of DWT-OFDM; it is very sensitive to Doppler frequency variations. Depending on the channel second path gain and delay there is a critical value of Doppler frequency for which increasing the SNR does not affect the BER performance of the system. This is produced by the loss in orthogonality between the carriers as a result of the multipath wireless channel. Proposed system has better performance than other systems; however for Doppler frequencies exceeding critical value FFT-OFDM outperforms proposed

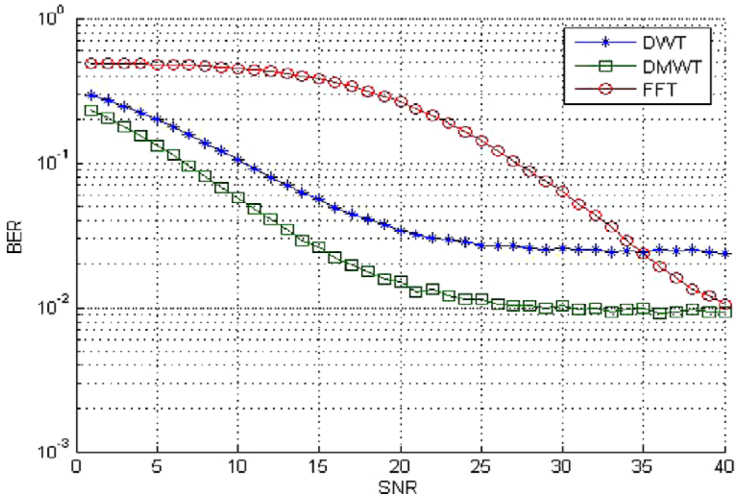

Fig. 8. The BER performance of DMWT-OFDM in selective fading channel at max Doppler shift = 1100 Hz.

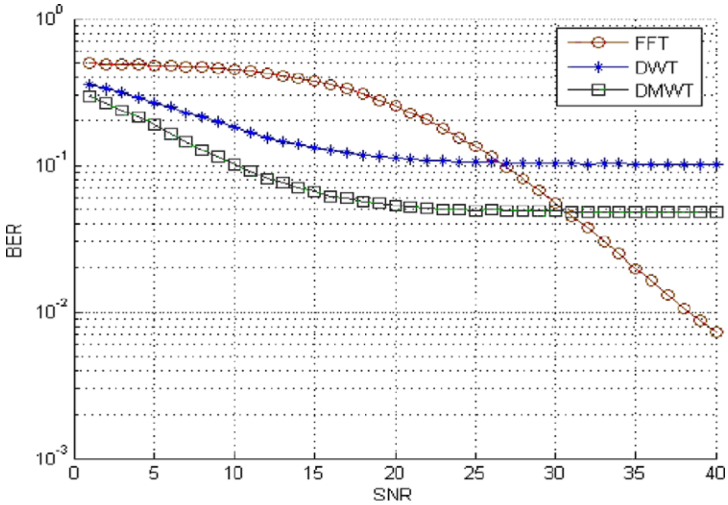

Fig. 9. The BER performance of DMWT-OFDM in selective fading channel at second path gain = −1 dB.

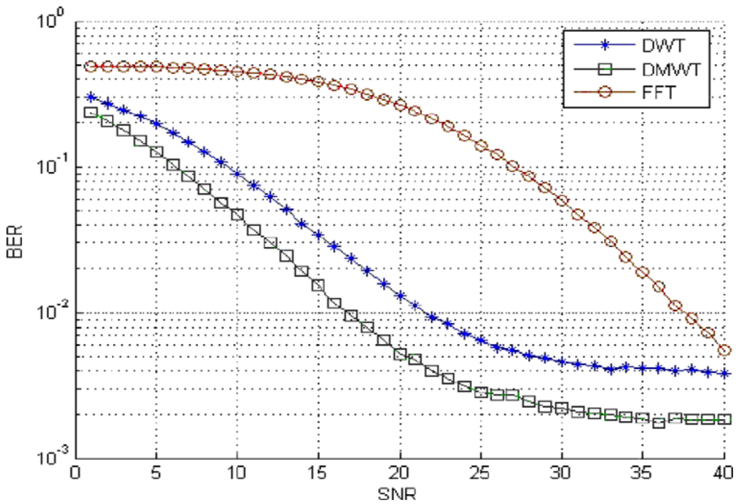

Fig. 10. The BER performance of DMWT-OFDM in selective fading channel at second path gain = −20 dB.

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system for very high SNR values ($SNR > 40$ dB) since increasing signal power does not solve the problem of interference. The Doppler frequency critical value increases with decreasing the second path gain and it is more sensitive to second path delay than second path gain variations.

5. Conclusions

In this paper, the DMWT-OFDM structure was proposed simulate and tested. Simulations provided proved that proposed design achieves much lower bit error rates and better performance than FFT-OFDM and DWT-OFDM assuming reasonable choice of the bases function and method of computations.

Proposed MWDT-OFDM give in AWGN channel $BER = 10^{-4}$ when $SNR = 11.5$ dB while wavelet based OFDM and FFT based OFDM give the same BER when $SNR = 18$ dB and 33 dB respectively. In FFC and selective fading channels Multiwavelet based OFDM also has performance better than the other two OFDM systems.

Proposed MWDT-OFDM systems is robust for multi-path channels and does not require cyclically prefixed guard interval, which means that it obtains higher spectral efficiency than conventional OFDM and it can be used at high transmission rates.

From obtained results it can be concluded, that SNR can be successfully increased using proposed multiwavelet designed method and using a desired multiwavelet bases function. Therefore this structure can be considered as an alternative to the conventional OFDM.

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