An Efficient Design of One and Two-Dimensional DWMT-MCM

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Original scientific article

***Abstract*—Primarily two areas of research progress are made in this paper: Discrete Wavelet Transform based Multicarrier Modulation (DWT-MCM), and the Discrete Wavelet Multitone based Multicarrier Modulation (DWMT-MCM). In this work, an efficient design of one and two-dimensional DWT-MCM is proposed for DWMT-MCM. Different channel conditions for different environments are simulated. Various wavelet families are employed with DWMT-MCM system. Additionally, bit error probability is compared to the familiar Orthogonal Frequency Division Multiplexing (OFDM) system for AWGN, Rayleigh flat fading, and frequency selective fading channels. The obtained outcomes demonstrate that the probability of error in the DWMT-MCM system is improved in many scenarios, even though the guard interval (Cyclic Prefix (CP)) is not used, which leads to increase the spectral efficiency. The results also demonstrate that there is an error floor for some families of wavelet transform. The obtained simulation results for DWMT-MCM system have significantly improved compared with conventional OFDM system in many scenarios and the proposed approach able to mitigate error floors introduced by channel variation effectively as well as the insufficient CP with high bandwidth efficiency.**

***Index Terms*—DWT, DWMT, MCM, Conventional OFDM, error floor.**

I. INTRODUCTION

FOR many decades, Single-Carrier Modulation (SCM) has represented an alternative approach for digital communication systems in different applications, such as in Asymmetric Digital Subscriber Line (ADSL) [1]. In some standards like LTE, single carrier frequency division multiple access (SC-FDMA) has been proposed for the uplink to avoid the drawbacks in MCM such as sensitivity to time and frequency synchronization and high ratio between peak-to-average power ratio (PAPR) [2]. Comparison between SCM and Multi-Tone Modulation depends on the channel degradations and the trade-off between complexity and the cost of implementation, i.e., MTM has some advantages in digital applications, but it needs greater cost in analog processing [3]. However, in the case of multipath propagation, an equalizer is required in the SCM system to minimize the Inter-Symbol Interference (ISI) [4]. In contrast, in a Multicarrier modulation (MCM) system it is not necessary to eliminate the ISI entirely, just to limit its length to less than the length of the guard interval (cyclic prefix (CP)) [5]. The requirement for the symbol duration to exceed the channel delay spread in SCM systems limits the achievable data rate [6]. FDM mitigates this limitation by splitting the available bandwidth into parallel subchannels, but inadequate carrier spacing leads to ICI. The use of guard bands reduces ICI at the cost of lower spectral efficiency and data rate [7].

Last two decades, orthogonal frequency division multiplexing (OFDM) systems have become one of the most exciting research topics in digital wireless communications. It was the first multicarrier scheme proposed for utilizing the white spaces in the spectrum [8]. Due to their ability to cope with different channel conditions such as attenuation, narrowband interference and multipath frequency selective fading, OFDM is a fundamental modulation scheme underlying multiple standards, such as *WiFi*, *WiMAX*, *DVB-T*, *LTE*, and *ADSL* [9]–[16]. It is a special form of the multicarrier modulation scheme which can solve both previous issues in digital communication systems. A large number of low data rate carriers (which greatly reduces ISI) are combined to form a high data rate system as in FDM [5]. On the other hand, the orthogonality of the parallel subcarriers acts to reduce the ISI even with close spacing between them. In general, OFDM system has many advantages in digital communication systems [17]. A particularly attractive feature is that they are capable of operating without a classic channel equalizer due to the orthogonality of the parallel subcarrier channels and because the selection of the guard interval is easily adjustable, perfect equalization will be achieved if the channel impulse response (CIR) is less than the length of the CP [18]. In addition, they maximize bandwidth efficiency and transmission rate, since adaptive modulation schemes can be applied to the maximum collection of narrow, closely spaced sub-bands which result from partitioning the channel into narrowband flat fading channels, which results in OFDM systems ability to work in frequency selective fading conditions [19].

On the other hand, there are many weaknesses in the OFDM systems. In the time-domain, OFDM systems create signals with high amplitude levels. This means that the RF power amplifiers require to be designed to work with high peak to average ratio (PAPR). Furthermore, the OFDM system is sensitive to the carrier frequency offset due to leakage of Fast

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Fourier Transform (FFT) which means losing some bandwidth to improve the system synchronization due to the effects of offsets between transmitted and received signals which lead to some interference to the received signal. Finally, to avoid interference, the symbol length must be longer than the length of CIR. This symbol length increase can be achieved by adding the guard interval which causes some losses in spectral efficiency of the OFDM system [5]. Furthermore, it has some defects have been identified in some applications such as cognitive radio (CR) system [20]. OFDM system contains some parts of spectral analysis such as FFT which needs to sense the spectrum in CR system. Due to the large side-lobes of the filter in OFDM system, significant interference will occur among the carriers of different secondary users as well as between secondary users and primary users in the wireless channel. In addition, CR requires synchronization for both uplinsk and downlink networks to avoid the ICI. To solve this problem, multiple-access OFDM or OFDM Access (OFDMA) has been proposed for CR systems [21] and it has become an alternative approach for many standards e.g. IEEE Standard 802.16e [22].

In some applications, owing to the above reasons, many researchers have tried to obtain an alternative multicarrier modulation approach instead of OFDM techniques such as Discrete Wavelet Transform (DWT) and Discrete Wavelet Muti-tone (DWMT). As an alternative to OFDM, Wavelet Transform (WT), is a suitable alternative for single and multicarrier applications and consider it a uniquely qualified to address a challenge to developing communication technologies capability of handling large volumes of information under different conditions such as power and bandwidth [23]. Superior rout investment under various intervention mediums has been employed by satisfying multi-rate undulation established on modification methods for both time and frequency proportions [24]. Multi-rate filter-banks and undulation transform in mediums symbolize and modification have been improved and inspected in various methodologies such as stretch subscription Code Division Multiple-Access (CDMA) and stretch echo pre-symbolized, fractal modification, and inflected multi-pitch modification [25]. The entailed elasticity of undulation modify with several motivating preferences have made it a strong candidate for multi-carrier plans [26]. Undulation packets as a multicarrier method with various access schemes have extensive to various users and cognitive radio enforcement [27]. Inherent orthogonality for multi-undulation has produced it to be more appropriate for both single and multicarrier modification methodologies a multi-servant CR connection and it also be able to minimize Multiple Access Interference (MAI) [28]. Recently, DWT is introduced in different research such as [29], [30]. A comparative performance analysis between DWT and FFT-OFDM is introduced in [29] under different channel conditions, while in [30] frequency domain equalizer is used to introduce the comparative between the two systems in Bit Error Rate (BER) under different channel conditions, Power Spectral Density (PSD), and PAPR.

In recent years, significant research efforts have been directed toward improving the performance of multicarrier communication systems through advanced signal processing and intelligent detection techniques. For example, wavelet-based deep learning models have been proposed to enhance signal detection in OFDM index modulation systems, showing promising improvements in detection accuracy and robustness under complex channel conditions [31]. In addition, efficient decoding methods for polar-coded OFDM systems operating over multipath fading channels have been investigated to improve the reliability and error-correction capability of multi-carrier transmission schemes [32]. These recent developments indicate the growing interest in integrating advanced detection and decoding strategies to enhance the overall performance of modern OFDM-based communication systems.

Unlike conventional DWT-OFDM implementations, the proposed DWMT-MCM framework introduces a multi-level decomposition and reconstruction structure for multicarrier signal generation and detection. This architecture enables efficient multicarrier transmission without the need for a cyclic prefix (CP), thereby reducing redundancy and improving spectral utilization. Furthermore, the proposed model integrates one-dimensional and two-dimensional DWMT processing to enhance signal representation and improve BER performance under different channel conditions. This multi-level structure distinguishes the proposed system from previously reported DWMT or wavelet-based OFDM implementations, which typically rely on single-level wavelet processing or CP-assisted transmission schemes.

The main contributions of this paper can be summarized as follows:

- An efficient design of one - and two-dimensional DWMT-MCM systems is proposed as an alternative to conventional FFT-OFDM without using a cyclic prefix.
- A detailed BER performance evaluation of the proposed DWMT-MCM system is carried out under AWGN, flat fading, and frequency-selective fading channels.
- The impact of different wavelet families on BER performance is investigated, demonstrating the superiority of Daubechies wavelets over biorthogonal and reverse biorthogonal wavelets.
- A multi-level reconstruction and decomposition model is introduced to mitigate BER degradation and error floors observed in certain wavelet families.
- A comparative BER-based analysis with conventional CP-OFDM highlights the performance gains of the proposed DWMT-MCM scheme.

The rest of the paper is organized as follows. Section II describes the principles of DWT-based MCM and the reconstruction and decomposition algorithms. Section III presents the proposed one- and two-dimensional DWMT-MCM models. Section IV discusses the simulation setup and BER performance results along with a comparison to conventional OFDM. Finally, Section V concludes the paper.

II. DISCRETE WAVELET TRANSFORM BASED MCM (DWT-MCM)

Recent studies have explored the integration of wavelet transforms in advanced multicarrier modulation schemes, demonstrating notable performance improvements in terms of bit error rate (BER) under various channel conditions. For example, wavelet-aided OTFS formats exhibit enhanced BER performance compared to conventional OTFS modulation [33]. Additionally, joint wavelet and sine transforms have been utilized to enhance OFDM system performance [34], and enhanced DWT-OFDM with wavelet domain equalization shows reduced BER compared to traditional equalizers [35]. Other work has applied wavelet transforms to SC-FDMA with index modulation to achieve competitive BER performance [36].

There are many benefits from utilizing the wavelets in a wireless communication system. First, create the subcarriers of symbol length and different bandwidths. Second, they fulfilled orthonormal base property and ideal reconstruction by incorporating the reconstruction filters (Low Pass Filter (LPF) and High Pass Filter (HPF)) as a Quadrature Mirror Filters (QMFs) or conjugate quadrature filters [37]. Structurally, the DWT-MCM system is analogous to the classical OFDM framework, except that the IFFT/FFT operations are substituted with IDWT/DWT processing at the transmitting and receiving ends. Figure 1, illustrates a typical block diagram of DWT-OFDM scheme. In this section, data rebuilding and deform features as the prime important issues will be discussed.

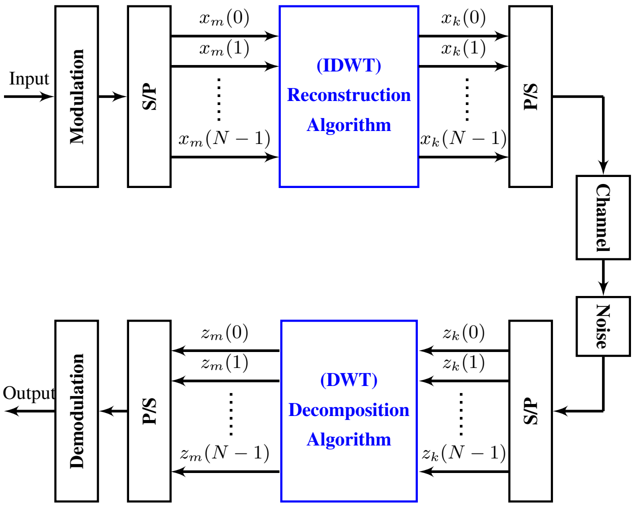

Fig. 1. A typical model of DWT based MCM transceiver.

A. *The Discrete Wavelet Transform*

Data reconstruction and decomposition properties are directly impacted by the wavelet. In wavelet transform, signals are demonstrated as a linear combination of wavelet and scaling functions. In wavelet function, the signals are represented at various frequencies and generated from the scaling function. That means the signal will be translated to time-frequency domain or time-scale domain. In this case, signal structures can be analyzed in different sizes by accurately locating the frequency construction with time. In addition, from a practical opinion, the DWT is incredibly much kind of like the Discrete Fourier Transform (DFT) [38]. That means both of them are orthogonal, the signal remains unchanged when passes twice through the transformation, and both are convolutions process. On the other hand, WT is based on a set of recursive difference equations while FT is based on a sinusoidal function.

$$\int \psi(t)\mathrm{d}t = 0 \tag{1}$$

The wavelet coefficients can be represented in different magnitude (scales) and location (time). In the reconstruction process, the performance sequentially starting with the largest scale and smallest time and progressing to the smaller scale and larger time [39]–[42]. After each iteration, the time is doubling and the scale is halving in size. The indices (j) and (k) represent the scale and time-shift parameters, respectively, and play a crucial role in ensuring system orthogonality. They are obtained through the dilation and translation operations applied to the wavelet function $\psi(t)$ or the scaling function $\phi(t)$. Referring to [43], the two-dimensional parametrization of wavelet function $\psi_{j,k}$ can be represented as:

$$\psi_{j,k}(t) = 2^{-j/2}\psi(2^{-j}t - k) \tag{2}$$

where, scaling index is defined as $j = J_1, J_2, ...J$ where $J = log_2(N)$, and N denotes the number of subcarriers. When $j = 1$, the system exhibits superior time localization at the expense of frequency resolution, whereas $j = J$ provides the highest frequency resolution with the poorest time localization [43]. Similarly:

$$\phi_{j,k}(t) = 2^{-j/2}\phi(2^{-j}t - k) \tag{3}$$

Using (2), members of the orthogonal wavelet family are obtained as:

$$\langle \psi_{j,k}(t), \psi_{m.n}(t) \rangle = \begin{cases} 1 & ,j = m \,\&\, k = n \\ 0 & ,otherwise \end{cases} \tag{4}$$

The transmitted signal can be represented as:

$$\begin{aligned} x(t) &= \sum_{j=J_1}^{J} \sum_{k=1}^{2^j} w_{j,k}\psi_{j,k}(t) \\ &+ \sum_{k=1}^{2^{J_1}-1} a_{J_1,k}\phi_{J_1,k}(t). \end{aligned} \tag{5}$$

where w and a represent the scaling and wavelet coefficients. Let $h(k) = c_k$ and $g(k) = (-1)^k c_{1-k}$ represent the low-pass and high-pass filters, respectively. The approximation and wavelet coefficients at scale j can be derived from the coefficients at the next finer scale $(j+1)$ using the following relations:

$$a_j(k) = \sum_m h(m - 2k)a_{j+1}(m) \tag{6}$$

$$w_j(k) = \sum_m g(m - 2k)w_{j+1}(m) \tag{7}$$

B. Reconstruction and Decomposition Procedures

In the transmitter of the DWT-based MCM system, the final processing stage is the inverse discrete wavelet transform (IDWT), which performs the signal reconstruction [37]. The implementation of both the IDWT and the DWT operations in the proposed DWMT-MCM system is illustrated in Figures 2 and 3. According to the Mallat algorithm [43], the number of decomposition or reconstruction stages is defined as $L = J - J_1$. During the reconstruction stage, the approximation and detail coefficients are first upsampled by a factor of two and then filtered by the corresponding low-pass and high-pass filters to generate the transmitted DWMT-MCM signal.

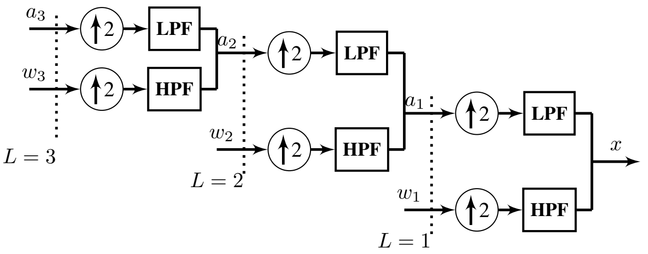

Fig. 2. IDWT implementation using filter banks.

The important note here is that the length of reconstruction filters is variable, and the variation in these filters lengths depends on the type of wavelet transform. This means that the length of the transmitted signal (x_k) is also variable. In general, by taking for granted that the reconstruction algorithm is single level, let L_{x_k} be the length of transmitting DWT-MCM signal, L_a be the length of approximate coefficients (a) (which also equals the length of w) and L_f the length of the reconstruction filters Lo_R and Hi_R. In other words, the length of transmitted signal depends on the extension mode, it means that if the extension mode is set to periodization (as in Haar or db1 wavelet types), L_{x_k} will be equal to the double length of the approximate or detail coefficients, otherwise, the length of the transmitted DWT-MCM signal will be computed as follows:

$$L_{x_k} = 2 \times L_a - L_f + 2 \tag{8}$$

In the DWT-MCM system, the length of the vector of approximation coefficients (L_a) equals the number of subcarriers (N), consequently, (8) can be written as:

$$L_{x_k} = 2 \times N - L_f + 2 \tag{9}$$

In the decomposition stage, the received signal is filtered using LPF and HPF and then downsampled by two to obtain the approximation and detail coefficients.

As in the reconstruction algorithm, let the decomposition algorithm be single level, and L_{ar} be the length of approximation coefficients (a) at the receiver (which also equals the length of w), which also depends on the extension mode of the type of the discrete wavelet transform. That means if the extension mode is set to periodization (as in Haar or db1 wavelet types), L_{ar} will be equal to the nearest integers greater than or equal to the half length of the received vector, otherwise, L_{ar} can be calculated as:

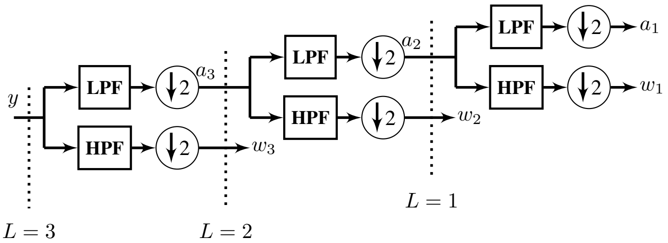

Fig. 3. DWT implementation using filter banks.

$$L_{ar} = \left\lfloor \frac{L_{Xk} + L_f - 1}{2} \right\rfloor \tag{10}$$

To ensure that L_{ar} is an integer, the elements between parentheses must be rounded to the closest integer less than or equal to its value.

III. Proposed Model of One and Two-dimensional DWT-MCM systems

In the DWT-MCM, the received signal has decomposed into its frequency components with an increasing frequency resolution as the frequency increases. It means that, to obtain a better analysis of the received signal, the DWT would be preferred to have a better resolution. Figure (4) illustrates the basic configuration of a proposed model for an efficient design of the two-dimensional (time-frequency) of the DWT based MCM system.

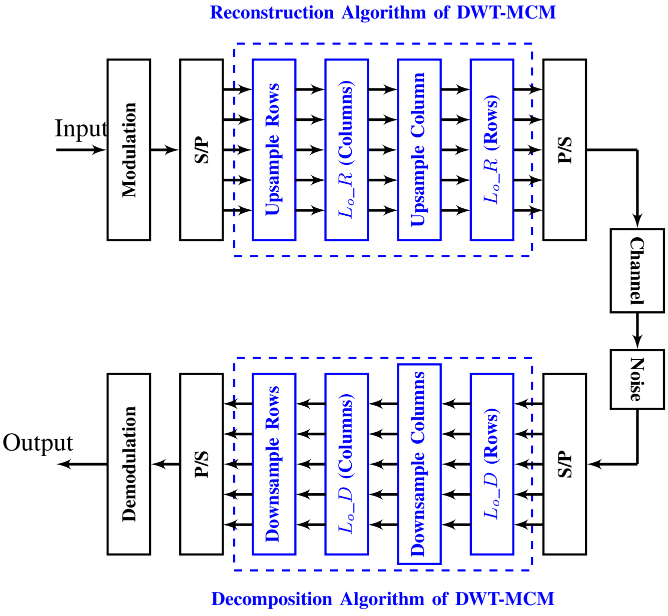

Fig. 4. Proposed model of 2-dimensional DWT based MCM systems.

At the transmitter side of the one-dimensional DWT-MCM proposed model, the modulated serial vector is upsampled by inserting zeros in odd-index. The signal obtained is convolved with the Lo-R (LPF) reconstruction filter coefficients to get the transmitted signal.

On the other hand, at the receiver side, the inverse operation is implemented to demodulate the received signal. The received signal is convolved with the decomposition filter coefficients Lo_D. The signal is downsampled by keeping the even-indexed samples to get the demodulated signal.

The data to be transmitted are first modulated by one of the modulation techniques. Next, the data are converted to parallel bit streams which are upsampled by inserting zeros at odd-indexed rows. After that, convolve each column of the resulting parallel signal with the coefficients of the reconstruction LPF (Lo_R). Zeros have inserted at odd-indexed columns to form new parallel data streams. Again, reconstruction LPF coefficients (Lo_R) are used by convolving them with each row of the signal to get transmitted signal.

In the receiver, the inverse operation is executed to demodulate the received signal. First of all, the received signal is converted into parallel form to convolve each row with the coefficients of the decomposition LPF (Lo_D). After that, columns of the resulting signal are downsampled by keeping the odd-indexed of them. Thereafter, the Lo_D filter coefficients are convolved with each column and the resulting rows are downsampled by keeping the odd-indexed rows to get the demodulated signal after converted it to a serial form.

The primary configuration of the DWMT model is depicted in Figure (1) with some different processing of the reconstruction and decomposition filters. Multi-bands have been used to reconstruct modulated data at the transmitter side and to decompose received data to manipulate it at the receiver side.

The procedure of the proposed n-level of the reconstruction algorithm of the DWMT based MCM system can be illustrated in algorithm (1). Firstly, the columns of the modulated signal matrix S with size of $[N \times N_s]$ has been up-sampled by 2 by inserting zeros in the odd-indexed columns. Thereafter, the resulting signal is converted into two parallel streams according to the number of subcarriers (N). These two parts are obtained from separate the odd and even rows of the resulting signal matrix. The odd and even rows are convolved with the reconstruction filter coefficients of the LPF (L_o_R) and HPF (H_i_R) respectively. Then, the two obtained signals are added together to construct the modulated signal which use in the next level. The processing steps in level one are repeated for all the next levels to obtain a serial vector which represents the transmitted signal. Moreover, the number of levels based on the number of subcarriers and equals $log_2(N)$. At i^{th} level, the obtained signals can be expressed as:

$$[S] = \left[\frac{N}{2^{i-1}} \times \left[2^{i-1}N_s + \left(2^{i-1} - 1\right)L_a - 2^{i-1} + 1\right]\right] \tag{11}$$

where, N_s represents the number of DWMT-MCM symbols and L_a the length of the coefficient vector of the LPF or HPF. After the upsampled columns of the S signal by 2, the obtained signal will become:

$$[S] = \left[\frac{N}{2^{i-1}} \times \left[2^{i}N_s + \left(2^{i} - 2\right)L_a - 2^{i} + 2\right]\right] \tag{12}$$

The approximation and details coefficients a and w matrices can be obtained by convolved the odd and evens rows S_e and S_o of the resulting signal in (12) with the reconstruction filter coefficients of the LPF (L_o_R) and HPF (H_i_R) respectively.

$$[a] = \text{conv}(S_o, L_o\_R) \tag{13}$$

$$[w] = \text{conv}(S_e, H_i\_R) \tag{14}$$

Again a and w matrices are added together to obtain the signal S which used as a modulated signal in the next level, where S can be expressed as:

$$[S] = \left[\frac{N}{2^{i}} \times \left[2^{i}N_s + \left(2^{i} - 1\right)L_a - 2^{i} + 1\right]\right] \tag{15}$$

At the desired m-level, where $1 \leq m \leq n$, if $m = n$ then the transmitted DWMT-MCM signal X can be expressed as;

$$[X] = [1 \times [NN_s + (N-1)L_a - N + 1]] \tag{16}$$

Otherwise, X at the m^{th} level can be obtained be converting S into a serial vector as:

$$[X] = \left[1 \times \left[NN_s + \frac{N(2^m - 1)}{2^m}L_a - \frac{N(2^m - 1)}{2^m}\right]\right] \tag{17}$$

Algorithm 1 Proposed n-level reconstruction algorithm.

```
Initialize: $i = 1$
Choose $m$-level, $1 \leq m \leq n$
while $i < m$ do
    $[S_1]$ = upsample columns of $[S]$ by 2
    $[S_o]$= Odd rows of $[S_1]$
    $[a] = \text{conv}(S_o, L_o\_R)$
    $[S_e]$= Even rows of $[S_1]$
    $[w] = \text{conv}(S_e, H_i\_R)$
    $[S_2] = [a] + [w]$
    if $i = m$ then
        $[X] = [S_2]$
    else
        $[S] = [S_2]$
        $i = i + 1$
    end if
end while
```

On the other hand, the proposed model of the decomposition algorithm is shown in algorithm (2). At the receiver side, the inverse operation is performed to manipulate the previous algorithm. The processing steps of the decomposition algorithm can simply be described as: Firstly, at the first level, convolve the received signal with the LPF and HPF filter coefficients vectors (L_o_D and H_i_D) in separated parts which used to obtain the the approximation (a) and the details (w) coefficients respectively. Next, downsample each part by keeping the even-indexed column. Then, in each part, keep part of the obtained matrix by removing the extensions which accorded due to the convolution with the filter coefficients. After that these two parts are collected to get a signal with double the number of rows, which is used in the next level. The odd rows represent the resulting signal of the approximation coefficients while the even rows represent the resulting signal from the details coefficients. Finally, all steps in the first level are repeated for all the subsequent levels to form parallel bit streams after the end of the final level, which are converted to serial form and demodulated and detected to calculate the bit error probability.

Algorithm 2 Proposed n-level decoposition algorithm.

```
Initialize: $i = 1$
Choose $m$-level, $1 \le m \le n$
while $i < m$ do
    $[a_1] = \text{conv}(Y, L_o\_D)$
    $[w_1] = \text{conv}(Y, H_i\_D)$
    $[a_2]$= Down sample of $a_1$ by 2
    $[w_2]$= Down sample of $w_1$ by 2
    $[a_3]$= Keep part of $a_2$
    $[w_2]$= Keep part of $w_2$
    Odd rows of $[Z] = [a_3]$
    Even rows of $[Z] = [w_3]$
    if $i = m$ then
        $[S] = [Z]$
    else
        $[Y] = [Z]$
        $i = i + 1$
    end if
end while
```

Again the steps of the decomposition algorithm can be expressed in a matrix form as:

Consider the noiseless channel, then the received signal Y is:

$$[Y] = \left[\frac{N}{2^i} \times \left[2^i N_s + \left(2^i - 1\right) L_a - 2^i + 1\right]\right] \tag{18}$$

To get the approximation coefficients a, first, convolve Y with the filter coefficients L_o_D and then down-sample the columns of the obtained signal by 2,

$$[A] = \text{conv}(Y, L_o\_D) \tag{19}$$

$$[A] = \left[\frac{N}{2^i} \times \left[2^i N_s + 2^i L_a - 2^i\right]\right] \tag{20}$$

Down-sample the columns by 2,

$$[a] = \left[\frac{N}{2^i} \times \left[2^{i-1} N_s + 2^{i-1} L_a - 2^{i-1}\right]\right] \tag{21}$$

After that keep part of the obtained signal by removing the extension due to the convolution process,

$$[a] = \left[\frac{N}{2^i} \times \left[2^{i-1} N_s + \left(2^{i-1} - 1\right) L_a - 2^{i-1} + 1\right]\right] \tag{22}$$

Similarly, the same process will be used to calculate the details coefficients w by convolving Y with HPF coefficients H_i_D, down-sample the columns and keep part of the obtained signal.

The signal Y that used in the next level will be obtained by inserting a and w in the odd and even rows,

$$[Y] = \left[\frac{N}{2^{i-1}} \times \left[2^{i-1} N_s + \left(2^{i-1} - 1\right) L_a - 2^{i-1} + 1\right]\right] \tag{23}$$

At the m^{th} level, Y will represent the estimated value of the modulated signal X which used to calculate the bit error rate after the demodulation process.

IV. SIMULATION RESULTS

A. BER Performance Evaluation

TABLE I
MAIN SIMULATION PARAMETERS

Parameter	Value
Modulation scheme	4-QAM
Number of subcarriers	128
Wavelet family	rbio3.3, bior5.5, Daubechies
Channel models	AWGN, Flat fading, EPA-LTE
EbN0 range	0–40 dB
Cyclic prefix	Not used (DWMT-MCM)

In this work, LTE downlink standard [13] is used with sufficient and insufficient CP in case of OFDM systems. in each frame, the total number of used and unused sub-carriers (FFT size) is 128 with (10 *ms*) frame duration, 1.25 MHz channel bandwidth, 15kHz sub-carriers spacing, and 6 resource blocks. the influence of multipath propagation and frequency-selective fading is studied and the results are obtained under the effect of the Maximum Doppler Shift (MDS) of diffuse components in (Hz) with channel gain and delay profiles of Extended Pedestrian A model (EPA).

As shown in Figure (5), the performance of FFT-OFDM and DWMT-MCM with 4-QAM modulation is evaluated over a flat fading channel. The DWMT-MCM scheme achieves superior performance compared to FFT-OFDM for all Daubechies wavelet families, whereas the application of biorthogonal and reverse biorthogonal wavelets results in inferior performance.

To enhance the DWMT-MCM system performance with the biorthogonal and reverse biorthogonal wavelet types. The proposed model which is presented above is used with M-level reconstruction and decomposition algorithms for the DWMT based MCM systems as shown in Figure (6)

Figure (7) depicts the simulation outcomes of the FFT-OFDM and the DWMT systems using 4-QAM modulation over the EPA-LTE multipath fading channel with all Daubechies wavelet type and MDS = 5. It is clear from this figure that the results of the DWMT outperform the conventional OFDM system, especially with using the proposed model for the reconstruction and decomposition algorithms.

To quantify the performance improvement, the proposed DWMT-MCM system was compared with conventional CP-OFDM under identical simulation conditions. The results indicate that the proposed approach achieves an SNR gain

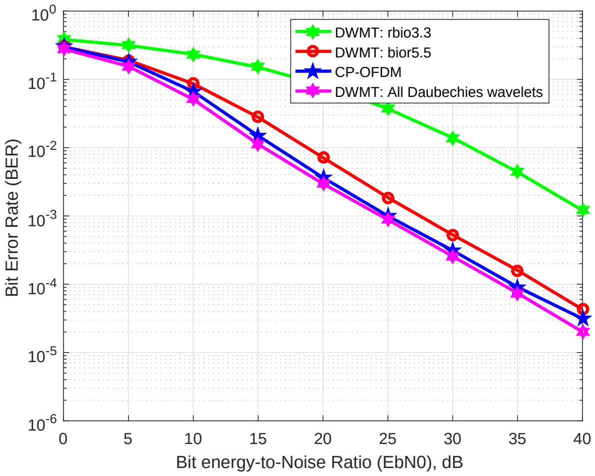

Fig. 5. BER performance comparison between DWMT-MCM and FFT-OFDM systems employing 4-QAM modulation over a flat fading channel.

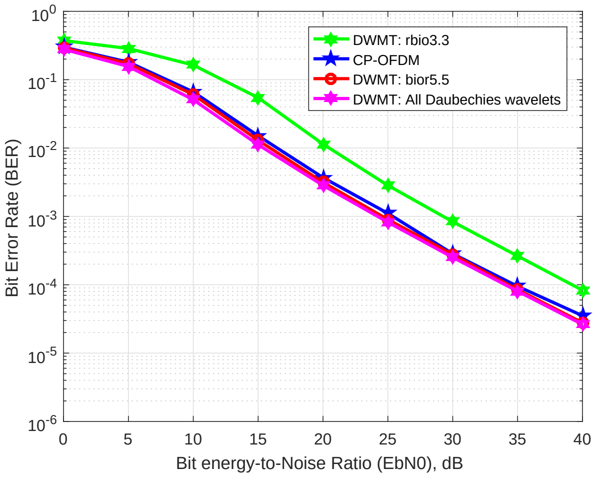

Fig. 6. BER performance comparison of DWMT-MCM and FFT-OFDM systems with the proposed model using 4-QAM modulation over a flat fading channel.

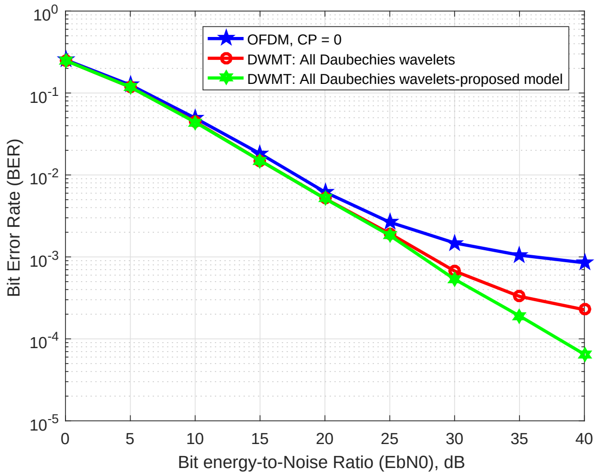

Fig. 7. BER performance comparison of DWMT-MCM and FFT-OFDM systems using 4-QAM modulation over EPA-LTE downlink channel.

of approximately 1–3 dB at a BER level of 10^{-3} depending on the channel scenario. Furthermore, the proposed system does not exhibit a noticeable error floor in the high-SNR region. This improvement is mainly attributed to the better time–frequency localization properties of Daubechies wavelets and the absence of cyclic prefix overhead, which enhances the effective signal structure.

Another important advantage of the proposed DWMT-MCM system is the improvement in spectral efficiency resulting from the elimination of the cyclic prefix. In conventional CP-OFDM systems, the cyclic prefix introduces redundancy that reduces the effective spectral efficiency.

The spectral efficiency of CP-OFDM is defined as:

$$\eta = \frac{N}{N + N_{CP}} \tag{24}$$

where N is the number of subcarriers and N_{CP} is the cyclic prefix length. Since the proposed DWMT-MCM system does not require a cyclic prefix, the effective spectral efficiency becomes higher compared with CP-OFDM under the same transmission parameters.

B. Comparative Analysis and Discussion

Table II summarizes the BER performance comparison between the proposed DWMT-MCM scheme and related multicarrier modulation techniques reported in the literature.

This subsection provides a combined comparative analysis and discussion of the obtained BER results in relation to existing multicarrier modulation schemes. The simulation results demonstrate that the proposed DWMT-MCM system, particularly when employing Daubechies wavelets, achieves lower BER compared to conventional CP-OFDM under identical channel conditions, despite operating without a cyclic prefix.

This subsection provides a combined comparative analysis and discussion of the obtained BER results in relation to existing multicarrier modulation schemes. The simulation results demonstrate that the proposed DWMT-MCM system, particularly when employing Daubechies wavelets, achieves lower BER compared to conventional CP-OFDM under identical channel conditions, despite operating without a cyclic prefix. This behavior can be attributed to the superior time–frequency localization and orthogonality properties of Daubechies wavelets, which enhance robustness against multipath fading.

Compared with recent wavelet-based multicarrier techniques, such as wavelet-aided OTFS systems reported in [33], the proposed DWMT-MCM approach offers a simpler multicarrier structure while still achieving competitive BER performance in fading channels. Although OTFS targets high-mobility scenarios, its increased receiver complexity distinguishes it from the proposed scheme, which is more suitable for low-to-moderate mobility environments.

Furthermore, hybrid OFDM schemes based on joint wavelet and sine transforms [34] and wavelet-domain equalization [35]

TABLE II
BER PERFORMANCE COMPARISON OF PROPOSED DWMT-MCM AND RELATED METHODS

Scheme	*CP Used*	*Channel Type*	*BER Performance*
Conventional CP-OFDM	Yes	AWGN / Fading	Baseline
Proposed DWMT-MCM (Daubechies)	No	AWGN / Fading	Improved
Wavelet-Aided OTFS [33]	No	High-Mobility Fading	Improved
Joint Wavelet–Sine OFDM [34]	Yes/No	AWGN / Fading	Improved
Enhanced DWT-OFDM Equalizer [35]	Yes/No	Fading	Improved

have shown BER improvements over conventional OFDM systems. However, these methods typically rely on additional processing stages or equalization algorithms. In contrast, the BER gains achieved by the proposed DWMT-MCM system arise inherently from the multiresolution nature of the wavelet decomposition without requiring complex equalization.

The observed BER degradation and error floors associated with biorthogonal and reverse biorthogonal wavelet families are consistent with their longer filter lengths and reduced time localization, which increase sensitivity to channel variations. The proposed multi-level reconstruction and decomposition model effectively mitigates these effects by improving signal representation across time and frequency domains.

Overall, the combined results confirm that the proposed DWMT-MCM scheme provides a favorable trade-off between BER performance, implementation simplicity, and spectral efficiency, making it a viable alternative to both conventional CP-OFDM and recent wavelet-based multicarrier modulation techniques.

V. CONCLUSION

In this paper, the DWMT based MCM systems have been presented as an alternative approach to the conventional OFDM system. In general, the simulation analysis has been obtained under different channel conditions using different types of wavelet transform. However, from the simulation analyses, the results such as bit error probability of the conventional OFDM are better compared with some types of DWT such as Biorthogonal and reverse Biorthogonal wavelet types. The simulation outcomes of Daubechies wavelet are better than that of CP-OFDM system. The system performance has been enhanced by employing the proposed model of the DWT-based MCM with m-level algorithm using biorthogonal and reverse biorthogonal wavelet types but still worse than that of CP-OFDM.

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