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Enhancing OFDM Performance Using Wavelet Transform Techniques in Wireless Systems

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Abstract: Orthogonal Frequency Division Multiplexing (OFDM) technique has attracted major interest because of its robustness to time selective channels and its aptitude to accomplish high data rate. OFDM is the fundamental solution in 4G and 5G systems due to its simplicity of implementation and effectiveness in severe environments. Traditionally the Fast Fourier Transform (FFT) algorithm is adopted to implement OFDM transmitter. Discrete Wavelet Transform (DWT) is recognized as an improvement to Discrete Fourier Transform; therefore, many academics proposed it as alternative approach to FFT in OFDM transmission system. We propose to study the impact of DWT on the performance of the OFDM transmission system considering various modulation techniques and order in noisy and fading environments. We implement two approaches namely OFDM-FFT and OFDM-DWT, their performances respective are studied and compared. Through simulation examples, we notice the improvements obtained by performing the wavelet transform. The wavelet-based OFDM techniques perform better than OFDM-FFT. The results obtained demonstrate the improvements achieved by adopting the wavelet transform relatively to the FFT for all evaluation metrics used. OFDM-DWT cancels interferences, as we can learn from constellation diagrams, where symbols are delimited in their original zones. OFDM-DWT performs the lowest bit error rate (BER) and a reduced Complementary Cumulative Distribution Function (CCDF) of the Peak to Average Power Ratio (PAPR).

Keywords: Orthogonal frequency division multiplexing (OFDM), Discreet wavelet transform (DWT), Wireless communications, Fast fourier transform (FFT)

Introduction

Wireless networks using Orthogonal Frequency Division Multiplexing (OFDM) offer excellent performance in dispersive multipath environments. OFDM allows increasing data rate and therefore spectral efficiency without compromising bandwidth OFDM benefit (Gruyer & Paillard, 2005; Gupta & Jha, 2015). OFDM transmission consists of distributing data over a large number of subcarriers, resulting in very narrow sub channels which ensures robustness in terms of spreading delay, thus reducing the transmission rate per subcarrier (Crawford et al., 2017 ; Gruyer & Paillard ,2005). OFDM technique is adopted in digital audio broadcasting standards for mobile telephony (DAB), digital terrestrial television (DVB-T), and high speed digital communications (ADSL) over the telephone local loop and its derivatives. (Banelli et al., 2014; Crawford et al., 2017 ; Gruyer & Paillard ,2005; Saadaoui, 2019).

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Owing OFDM advantages such as spectral efficiency, robustness to multipath fading, and ease of implementation using the Fast Fourier Transform, OFDM suffers from limitations, including high Peak-to-Average Power Ratio (PAPR), spectral leakage, and sensitivity to synchronization. Discrete Wavelet Transform (DWT) has been proposed as an alternative to overcome these issues errors (Almutairi & Krishna, 2022; Banelli et al., 2014; Veena & Swamy,2011). Wavelet-based OFDM can ensure time-frequency localization, improve spectral containment, and reduce PAPR due to the use of overlapping wavelet functions and suppression of cyclic prefix (Almutairi & Krishna, 2022; Banelli et al., 2014; Ramadan & Hassan,2025; Saadaoui, 2019; Veena&Swamy,2011).

There is a multitude of wavelet functions; Haar wavelets are the simplest, Daubechies wavelets, allow the application of filters of limited size, another wavelet family is the spline family, Depending on the problem to be solved, different wavelet families are used based on their qualities (Bouzida, 2008; Guo et al.,2022; Misiti et al.,2009; Ramadan & Hassan,2025; Saadaoui, 2019). OFDM systems can be designed with greater freedom using discrete wavelet transform; the wavelet shape can be carefully constructed to have the least possible distortion (Ramadan & Hassan, 2025; Saadaoui, 2019). Numerous studies have shown that wavelet-based multicarrier methods reduce ICI and ISI better than conventional FFT-based systems (Almutairi & Krishna, 2022; Hassan, 2019; Guo et al., 2022; Misiti et al., 2009; Ramadan, 2025; Saadaoui, 2019; Veena, 2011).

Wavelets subcarriers with varying bandwidths and symbol lengths can be created using the wavelet transform. The ability of wavelets to organize time-frequency tiling in a way that minimizes channel disturbances, noise, and inter-symbol interference makes them very attractive for telecommunication system design (Almutairi, 2022; Ramadan & Hassan, 2025; Saadaoui, 2019). Wavelets add a new level of signal diversity to cellular communication systems, allowing neighbouring cells to be labelled with different wavelets to reduce inter-cell interference (Guo et al.,2022; Ramadan & Hassan,2025).

Within this paper, we present a comparative study and performance analysis of FFT and DWT-based OFDM systems using MATLAB simulations. We use many metrics such as constellation diagram, BER and CCDF of PAPR to assess the performances of the mentioned systems. Through simulation results, we highlight the abilities of wavelet-based OFDM structures for enhancing the effectiveness and consistency of the OFDM system.

Theoretical Background of FFT-OFDM and DWT-OFDM

Background of FFT-OFDM

In OFDM system, the whole signal X(t) corresponding to all N symbols reassembled into one symbol OFDM is given by :

$$X(t) = \sum_{k=0}^{N-1} c_k e^{j2\pi f_k t} \quad (1)$$

Multiplexing is orthogonal the $f_k = f_0 + \frac{k}{Ts}$; T_s symbol duration, f_0 is the first carrier frequency, then:

$$X(t) = e^{j2\pi f_0 t} \sum_{k=0}^{N-1} c_k e^{j2\pi \frac{kt}{T_S}} \quad (2)$$

The received signal, over a symbol duration T_S can be expressed as:

$$Y(t) = \sum_{K=0}^{N-1} c_k H_k(t) e^{j2\pi f_k t} \quad (3)$$

$H_k(t)$ is the channel transfer function at the frequency f_k at time t. $H_k(t)$ varies slowly and can be assumed to be constant over the symbol period T_S (T_S<< 1/ Bandwidth). Then the demodulation process is performed among N subcarriers.

Channel impairments can cause a loss of orthogonality, between carriers and lead to interference between carriers (ICI: Inter Carrier Interference), or interference between symbols (ISI: Inter Symbol Interference). Guard intervals at each OFDM symbol avoid this problem (Crawford et al., 2017). The orthogonality condition shows that:

$$\frac{1}{T_s} \int_0^{T_s} e^{2j\pi(k-i)\frac{t}{T_s}} dt = \begin{cases} 0 \ , \ if\ k \neq i \\ 1 \ \ ,if\ k = i \end{cases} \quad (4)$$

$$\frac{1}{T_s}\int_0^{T_s} y(t)e^{-2j\pi f_i t}dt=\frac{1}{T_s}\sum_{k=0}^{N-1}\int_0^{T_s} C_k H_k e^{2j\pi(k-i)\frac{t}{T_s}}dt=C_i H_i \quad (5)$$

Background of DWT-OFDM

We give an insight on Discrete Wavelet Transform (DWT), for implementing an OFDM system. In the wavelet-based OFDM called OFDM-DWT, complex time windowed exponentials in FFT are replaced by wavelet carriers, at different scales 'j' and positions on the time axis 'k'. These functions are generated by the translation and dilation of a single function, called 'mother wavelet', denoted ψ (t):

$$\psi_{J,K}(t) = 2^{-j/2}\psi\,(2^{-j}t - k) \quad (6)$$

The time localization (k) and the scaling index (j) ensures orthogonality. Wavelet carriers exhibit better time-frequency localization relatively to FFT, with a comparable implementation complexity (Guo et al., 2022).
The orthogonality is achieved by generating the members of a wavelet family, according to the following:

$$\langle \psi_{j,k}(t), \psi_{m,n}(t)\rangle = \begin{cases} 1, & j = m \;\; et \; k = n \\ 0, & otherwise \end{cases} \quad (7)$$

Thy constitute an orthonormal basis of $L^2(R)$, if a finite number of scales j ∈ Z are considered. In this context, a scaling function Φ (t) is used. The OFDM-DWT symbol considered as a weighted sum of the carrier, wavelet, and scale, as expressed by equation (8). This corresponds to the inverse discrete wavelet transform IDWT (Inverse Discreet Wavelet Transform).

$$X(t) = \sum_{j\leq J}\sum_k w_{j,k}(t).\Psi_{j,k}(t) + \sum_k a_{J,k}\Phi_{J,k}(t) \quad (8)$$

The data symbols is a sequence of wavelets $w_{j,k}$ and approximation coefficients $a_{J,k}$. To perform the inverse discrete wavelet, transform IDWT, the filter bank-based Mallat algorithm is used (Bouzida, 2008; Misiti et al.,2009). The filter output gives the OFDM-DWT symbol, the lack of the cyclic prefix increases the spectral efficiency (Almutairi & Krishna, 2022; Ramadan&Hassan,2025;). Figure 1 shows the Block diagram of an OFDM-DWT system.

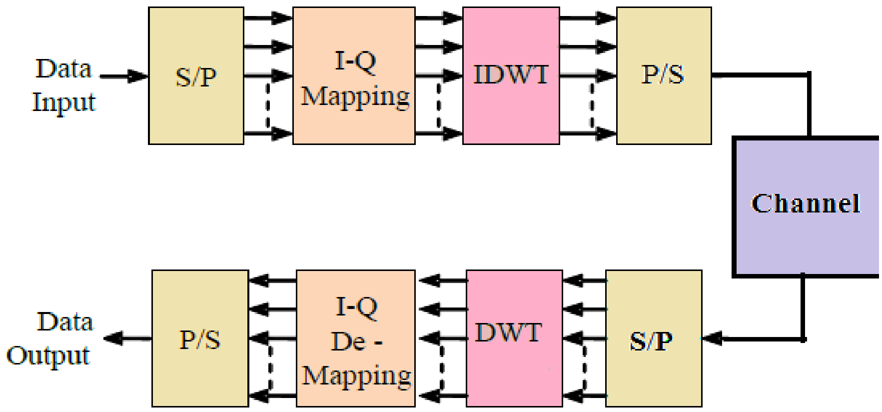

Figure 1. Block diagram of an OFDM-DWT system

In FFT-OFDM, there are M independent sub-channels via an IFFT operation with $K = 2^M$ points. To maintain the same data rate in wavelet systems, K independent sub-channels are multiplexed together via an IDWT operation with K points. Wavelets such as Harr or bi-orthogonal can be used to implement the DWT-OFDM system. Wavelet-based OFDM is implemented via overlapping waveforms to maintain the data rate. In this context, the use of the cyclic prefix makes no sense (Almutairi& Krishna, 2022; Ramadan, &Hassan 2025)

Results and Discussion

During simulations, we perform many wavelet type; Haar and bi-orthogonal gives the best results, nevertheless, Haar surpass in somme scenarios, that we adopted in our simulations.

Constellation Diagrams of OFDM-FFT and OFDM-DWT

We study the performance of the systems in giving output constellation free of distortion, noise and interferences. Figure 2. Shows the OFDM-FFT and OFDM-DWT constellations for 4-QAM and 16-QAM modulation considering an SNR of 15dB and 25dB.

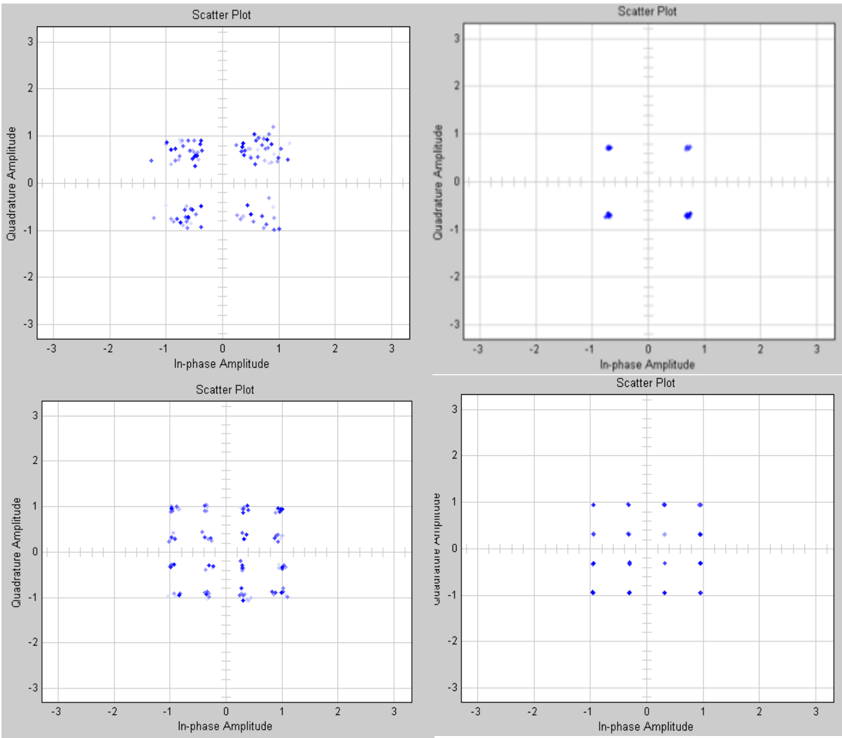

Figure 2. Constellation diagram: top left, FFT-OFDM and top right DWT-OFDM; 4-QAM, SNR=15 bottom left, FFT-OFDM and right below DWT-OFDM; 16-QAM, SNR=25dB

Through Figure 2 we observe that symbol dispersion is more pronounced for low Signal-to-Noise Ratio (SNR=15dB), for OFDM-FFT compared to OFDM-DWT. A noticed improvement is observed for the SNR of 25dB for the OFDM-FFT and OFDM-DWT, furthermore, the dispersion is completely canceled for the OFDM-DWT and symbols are delimited in their original locations. This highlights OFDM-DWT's ability to combat the effects of interference compared to ODFM-FFT.

Bit Error Rate (BER) Performance

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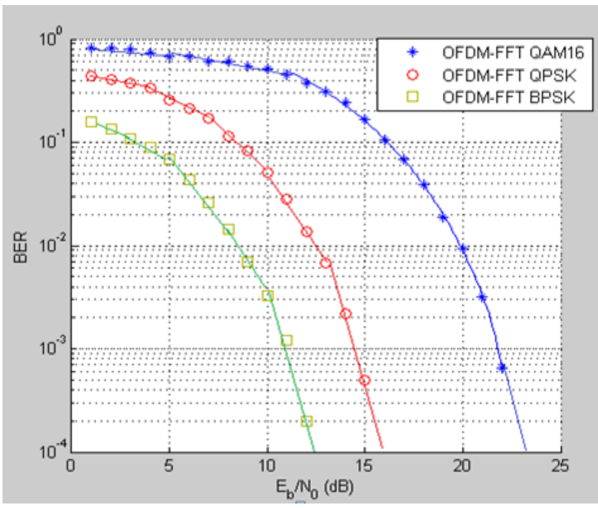

Figure 3. Bit error rate of OFDM- FFT for BPSK, 4-QPSK and 16-QAM modulation

We study bit error rate (BER) performances of OFDM-FFT for a variety of SNR values. Figure 3 Shows the BER achieved by OFDM-FFT for BPSK, 4-QAM and 16-QAM modulation. We study bit error rate (BER) performances of OFDM-DWT for a variety of SNR values. Figure 4 Shows the BER achieved by OFDM-DWT for BPSK, 4-QAM and 16-QAM modulations.

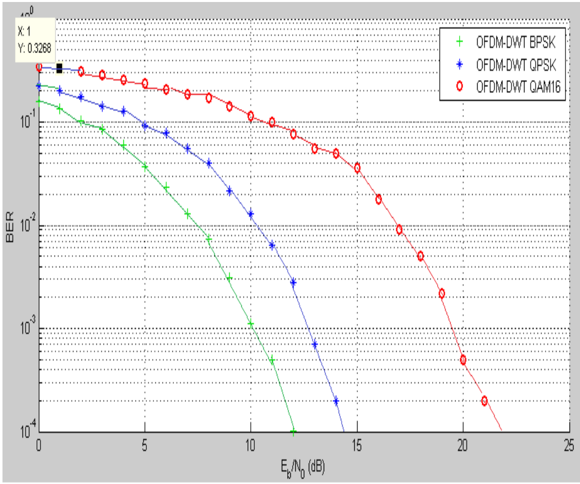

Figure 4. Bit error rate of OFDM-DWT for BPSK, 4-QPSK and 16-QAM modulation

As we can perceive at the BER of 10^{-4}, a transmission using BPSK can achieve an SNR of 12dB and 13dB for OFDM-DWT and OFDM-FFT respectively. Therefore, using BPSK improves BER in a noisy channel. On the other hand, a transmission using QPSK can achieve an SNR of more than 14dB and 16dB, for OFDM-DWT and OFDM-FFT, respectively. We notice that for a low-noise channel, transmission capability can be increased when using 16 QAM starting at SNR of more than 20 dB and 23 for OFDM-DWT and OFDM-FFT, in order. We can also learn through these curves that OFDM using DWT always provides the lowest error rate relative to OFDM using FFT. We also observe that, the BER gap between OFDM-FFT and OFDM-DWT increases further for QPSK (2dB) and attain (5dB) for lower SNR, in QAM-16 modulation.

CCDF of PAPR

We give a study of the complementary cumulative distribution function (CCDF) of the peak to average power ratio (PAPR) through CCDF curve. This metric shows the probability that a signal's power is equal or exceed a certain value. As we can perceive on Figure4, OFDM-FFT curve shifts to the right more then OFDM-DWT, indicating a higher PAPR when compared to OFDM-DW.

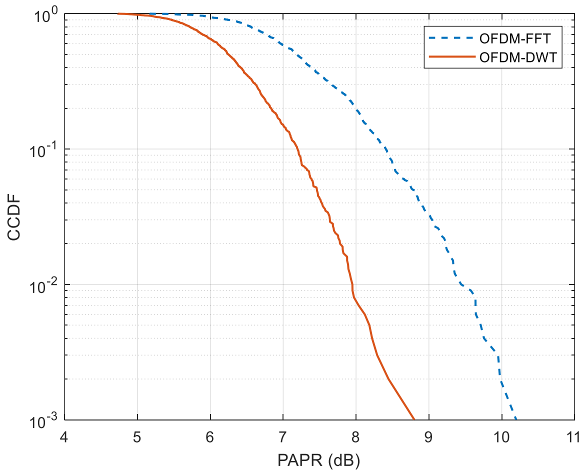

Figure 5. CCDF of PAPR: OFDM- FFT and OFDM-DWT

We can also observe an improvement of more than 1dB procured by OFDM-DWT over the OFDM-DWT. At a CCDF of 10−3, OFDM-DWT exhibits a PAPR of 8.8 dB, while OFDM-FFT shows a PAPR of 10.2 dB, in other words; OFDM-DWT attain only 8.8 dB of PAPR whereas OFDM-FFT 10.2 dB with 0.1% probability. Consequently, OFDM-DWT exhibits a better PAPR behavior when compared to the OFDM-FFT.

Conclusion

We discussed the fundamentals of OFDM-FFT and OFDM-DWT, and presented theirs performances through the examination of constellation diagrams, Bit Error Rate (BER) and CCDF of PAPR. We highlighted the impact of using wavelets on the performance of the OFDM transmission system in Gaussian environment. We found that the symbol constellation in the case of the OFDM-DWT system are delimited in their original zones and the dispersion is completely canceled. This highlights OFDM-DWT's ability to combat the effects of interference compared to ODFM-FFT. Improvements are also noticed in BER, where OFDM using DWT providing the lowest BER for all type of modulation. When studying the CCDF of PAPR an improvement is also noticed for the OFDM-DWT over the OFDM-FFT. CCDF curve of the OFDM-FFT shifts to the right more than The CCDF curve of the OFDM-DWT, indicating that it produce a higher PAPR when compared to OFDM-DW. The OFDM-FFT remains the dominant multicarrier modulation in wireless systems. Furthermore DWT-OFDM offers favorable benefits, justifying further exploration as a candidate waveform for beyond-5G.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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