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Performance Analysis Antenna Diversity Technique with Wavelet Transform Using Array Gain for Millimeter Wave Communication System

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Abstract: Utilizing antenna diversity techniques has become a well-known approach to improve the performance of wireless communication systems. Multiple antenna arrays with half-length spacing, such as a uniform linear array (ULA), have been taken into consideration. Since 60 GHz is an unlicensed frequency band and ideal for local propagation, it is where the technology is being used. The transmitter and receiver both accomplish QAM modulation and demodulation. The performance in terms of bit error rate (BER) was tested in MATLAB simulation software for all antenna diversity scenarios: the single input and single output (SISO) DWT, multiple input and single output (MISO) DWT, single input and multiple output (SIMO) DWT, and multiple input and multiple output (MIMO) DWT. The MIMO DWT was shown to be the best of them. The performance of MIMO OFDM using various wavelets was also simulated, and the performance of the Haar wavelet transform was 2 dB better than that of the other wavelet transform. Compared to simulation results, the analytical results showed good agreement with little discrepancy.

Keywords: SISO; SIMO; MISO; MIMO; BER; antenna arrays

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1. Introduction

The development of millimeter wave technologies has improved the functionality of wireless networks. It is now possible to meet the requirements for millimeter wave communication systems, such as high data rate, security, mobility, and spectral efficiency. In addition to increased system performance, success can be attributed to diversity approaches, wavelet transforms, coding algorithms, and other developing technologies. Future generations are considering wavelets because of their flexibility, which increases spectral efficiency. As the number of users for wireless communication quickly grows, many antennas are becoming utilized at the transmitter and receiver to maximize efficiency. MIMO antenna diversity is therefore essential for millimeter wave communication systems to boost capacity and minimize signal loss. The MIMO diversity technique was shown to outperform other diversity techniques when they were compared in for millimeter wave communication networks. Since millimeter wave wavelengths are short, numerous antenna arrays that operate at high frequencies have been used for short-range propagation systems.

An overview of the literature is presented in Section 2, followed by a detailed description of the methodology and the system model of the technique in Section 3. In Section 4, we discuss and compare the results obtained using the technique.

2. Literature Review

The fifth generation (5G) of wireless communication systems will primarily use millimeter wave (mm wave) technology due to the band's potential for high data rates, mobility, and low energy consumption [1]. One of the key criteria for future wireless communication networks is an increase in spectral efficiency. The signal loss caused by channel propagation at the receiver is one of the current main research issues. When a system employs millimeter waves, the received signal becomes more sensitive since the frequency ranges from 3 GHz to 300 GHz. Discrete wavelet transforms are employed in orthogonal frequency division multiplexing (OFDM) systems to increase spectral efficiency (DWT). Therefore, wavelet transforms can be used to design antenna diversity techniques to enhance system performance and spectrum efficiency [2].

Different modulation methods enhance the performance of MIMO wireless channels. In MISO channels, transmit diversity is achieved using a sophisticated algorithm, whereas SIMO channels use receiver diversity schemes such as MRC and selection diversity [3–6]. However, because it necessitates inserting a cyclic prefix at the transmitter and removing it at the receiver, conventional OFDM employing fast Fourier transform (FFT) still has the disadvantage of lowering spectral efficiency. As it does not require the use of a cyclic prefix, discrete wavelet transformations (DWTs) are employed as a substitute for FFTs to boost spectrum efficiency. One of the limitations of wireless signal transmission can be multipath fading, the result of which is that the signal at the receiver could be distorted and loud. Therefore, antenna diversity, or having several inputs and outputs, can enhance a receiver's BER performance. To increase spectral efficiency and decrease BER, MIMO diversity with wavelet transform must be applied in millimeter wave communication systems.

The primary method for raising spectral efficiency and enhancing system performance in mobile communication is the use of smart antenna systems. In order to create required radiation patterns, smart antennas often consist of a number of radiating elements (i.e., array antennas) whose individual excitation can be controlled by a DSP (digital signal processor) [7]. In 5G wireless communication networks, antenna arrays are now a part of the default configuration. Since an antenna array contains several elements, it can be used as an MIMO system in wireless communications systems. By examining the redundancy across the several broadcast and receive channels, antenna arrays can be used to improve the performance of systems in terms of BER. They also enable a system's spatial data to be reused in order to increase coverage.

The unlicensed spectrum at 60 GHz supports high rates, and many researchers are using the 60 GHz frequency because it also provides license free communication and improve efficiency [8–12]. Hence, for our investigation, the signal was deployed at 60 GHz and a two-element uniform array antenna array with half-length spacing was used to provide the MIMO diversity technique. The performance of OFDM with wavelet transform is better than that of the fast Fourier transform because it does not require the insertion of a cyclic prefix [13–19]. Studies of MIMO diversity with wavelet transform have shown that it can improve the performance in terms of BER compared with SISO channel diversity, and it has been suggested to be able to meet the demands of wireless networks [20–23]. Therefore, an MIMO diversity technique with OFDM can be used to improve the performance in terms of BER [24,25].

3. System Model and Methodology

Figure 1 represents the studied system model's overall view. The receiver block receives the data after they have been created and transmitted to the transmitter block and channel. In the next section, we provide a detailed explanation of each block. By comparing the computed BER with the actual data that are transmitted to the channel, the biterr function from MATLAB is used to calculate the BER at the receiver.

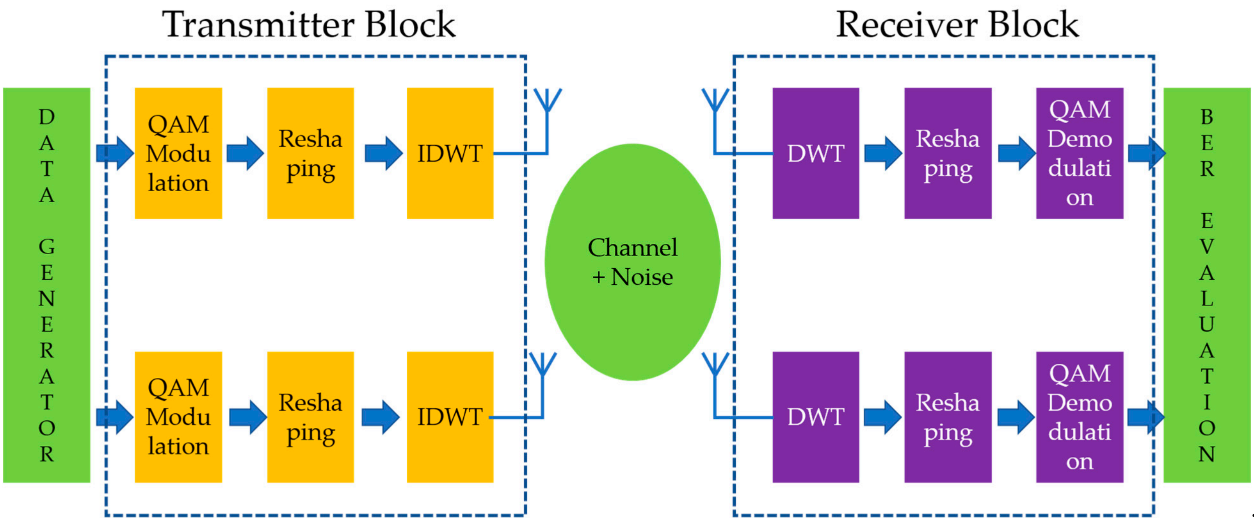

Figure 1. Overview of the system model.

3.1. Transmitter Block

The transmitter block of the proposed technique is highlighted in Figure 1. Using 16 QAM modulation, the generated data are modulated. The data are then reshaped using a number of symbols. The definition of approximation coefficient vectors (CA) involves transposing the reshaped data. Detailed coefficient vectors (CD) are created by transposing the reshaped data and adding zeroes to their length. Thus, if XX is the data after reshape,

$$\mathrm{XX} \ = [\mathrm{d1}, \mathrm{d2}, \ldots\ldots\ldots\ldots\ldots \mathrm{dn}] \tag{1}$$

CA can be define as by taking its transpose,

$$\mathrm{CA} = \mathrm{XX}^{\mathrm{T}} \tag{2}$$

Then, CD can be expressed as by taking its transpose. Here, l is the length,

$$\mathrm{CD} \ = [0, 0, 0 \ldots\ldots \mathrm{l(CA)}]^{\mathrm{T}} \tag{3}$$

Finally, a built-in MATLAB function of IDWT is used to conduct a one-dimensional reconstruction with respect to the wavelet type using the vectors representing the approximation and detailed coefficients. We chose the dB8 wavelet type for our study. The channel receives the data that have been rebuilt and are used for transmission. Therefore, employing IDWT eliminates the need for cyclic prefix insertion, improving spectral efficiency.

3.2. Receiver Block

Figure 1 highlights the receiver block of the proposed approach. The channel-received data are passed via the built-in dwt MATLAB function, which (depending on the wavelet type and including the approximation and detailed coefficient vectors cA and cD, respectively) returns the one-dimensional wavelet transform. The type of wavelet used in the transmitter is also used here. Since cA and cD are both the same length, only cA is reshaped and cD is disregarded. The reshaped data are then demodulated using 16 QAM demodulation. The biterr function is applied to the demodulated data to determine the BER, and the results are shown using the SNR range. The findings are represented in terms of BER and lead to reductions in BER, which improves system performance.

When employing the wavelet transform, it is vital to recover the original signal from the wavelet coefficients. To achieve perfect reconstruction, certain conditions must be met by the analysis and filters [26]. Let G(z) and, $\mathrm{G}^*(\mathrm{z})$ represent low pass and synthesis filters, respectively, and H(z) and, $H^*(z)$ represent high pass and synthesis filters, respectively. The filters must then meet the following two requirements:

$$G(-z)G^*(z) + H(-z)H^*(z) = 0 \quad (4)$$

$$G(z)G^*(z) + H(z)H^*(z) = 2Z^{-d} \quad (5)$$

According to Equations (4) and (5), the reconstruction is aliasing-free and the amplitude distortion has an amplitude of one. When the analysis and synthesis filters are switched, the perfect reconstruction condition does not change.

3.3. Channel Model

The conventional layout for 5G wireless communication systems now includes antenna arrays. Such wireless communications systems are sometimes referred to as multiple input and multiple output (MIMO) systems since an antenna array contains several elements. By examining the redundancy across the various transmit and receive channels, antenna arrays can aid in increasing the SNR. Additionally, they enable the system's spatial and temporal information to be recycled in order to increase coverage. The system is deployed at 60 GHz in the line-of-sight propagation (LOS) and multipath propagation channel. The LOS path is the direct path between the transmitter and receiver assuming perfect channel conditions. Scatters are placed in the channel between transmitter and receiver, and when the data are passed through each scatter, they form a path that results in a multipath propagation channel.

The transmitter is placed at a distance of 100 m in an indoor scenario. Antenna arrays have been used to reduce the BER as they consist of multiple elements that provide multiple inputs and outputs [27]. To investigate the performance with wavelet transform, the considered transmitter and receiver antenna array was a two-element ULA with half-wavelength spacing. The channel matrix for the MIMO channel with transmit and receive array for the millimeter wave channel model was adopted with the Scatteringchanmtx MATLAB function, The function returns the channel matrix components based on elements of transmit and receive array. The received signal Y can be given as

$$[Y] = [hchan] \times [x] + [n] \quad (6)$$

The hchan can be 2×2 channel matrix for MIMO channel, and it can be 1×2 or 2×1 channel matrix for SIMO and MISO channels, respectively; n is the AWGN noise. The transmit and receive element position are found based on the wavelength, which depicts the frequency of millimeter wave communication system.

3.4. Analysis of Proposed Technique

In this section, the BER analysis of the proposed technique is discussed. The performance is analyzed for the MIMO channel with a ULA having half-length spacing.

The received signal is expressed mathematically as

$$Y(t) = s(t) + n(t) \quad (7)$$

If the r(t) is the impulse response of the ULA channel is given by

$$r(t) = e^{-i2\pi \frac{x}{\lambda}} \quad (8)$$

Therefore, the equation can be written as

$$y(t) = r(t) \times s(t) + n(t) \quad (9)$$

where n(t) is the noise and s(t) represents the data transmitted. The error p_e for DWT-OFDM is given by [28]

$$p_e = \frac{\sqrt{M}-1}{\sqrt{M}\log_2\sqrt{M}}\text{erfc}\left[\sqrt{\frac{3\log_2 M\frac{E_b}{N}}{2(M-1)}}\right] \tag{10}$$

where M is the M array QAM modulation and $\frac{E_b}{N}$ is SNR.

The BER for the millimeter wave MIMO LOS is given by [29]

$$\text{BER} = P_e\left(\frac{E_b}{N}\frac{m}{n}\right) \tag{11}$$

Then BER for the MIMO DWT can be expressed as

$$\text{BER} = \frac{1}{2}P_e\sqrt{\left(\frac{E_b}{N}\frac{m}{n}\right)} \tag{12}$$

where m is the number of transmitter antennas and n is number of receiver antennas.

4. Results and Discussion

In this section, the effectiveness of wavelet transform with various diversity techniques and the effectiveness of various wavelet families for MIMO diversity techniques are explored. Additionally, analytical findings are used to validate the observed performance. Our work was purely a simulation, and experimental work was out of our scope due to the constraints of equipment and cost. In order to validate our simulation work in accordance with theoretical work, we compared our simulation results with the mathematical model described in Section 3.4 so that the parameters of SNR and BER were correctly measured.

4.1. SISO and SIMO

Figure 2 displays the BER of SISO and SIMO channel diversity performance. In this case, the data were transmitted over a single channel at the transmitter, while receive diversity was used at the receiver with a uniform linear array antenna that offered array gain to increase SNR and reduce BER. Table 1 lists the simulation parameters. The wavelet family we considered for our research was dB8, and the modulation strategy we used was QAM modulation. The performance of the SIMO DWT, with an SNR of 13.5 dB at 10^{-3} BER, was better than that of the SISO DWT with wavelet transform and much greater than the minimum 13.5 dB required for mm wave communication systems.

Table 1. Simulation parameters for SISO and SIMO.

Simulation Parameters	SIMO DWT	SISO DWT
Modulation Scheme	QAM 16	QAM 16
DWT family	dB8	dB8
Type of channel	AWGN	AWGN
Number of antennas	1 × 2	1 × 1
SNR range	[0:20]	[0:20]

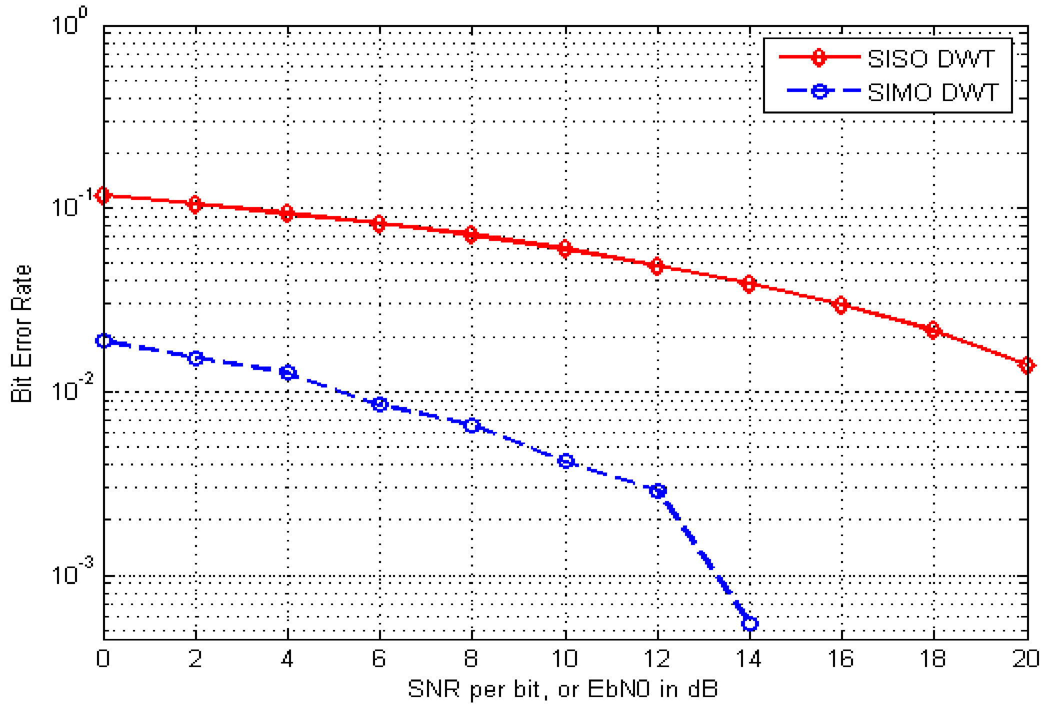

Figure 2. SIMO diversity with DWT-OFDM.

4.2. SISO and MISO

Figure 3 displays the wavelet-transformed BER performance for the SISO and MISO channel diversity techniques. Data were transmitted through the channel and received by the receiver through the signal output channel when transmit diversity was used at the transmitter. Because of the array gain at the transmitter, the SNR was increased, which reduced the BER. Because the SNR value at 10^{-3} for the MISO DWT was 12 dB and that for the SISO DWT was higher than 12 dB, the MISO DWT performed better than the SISO DWT diversity approach.

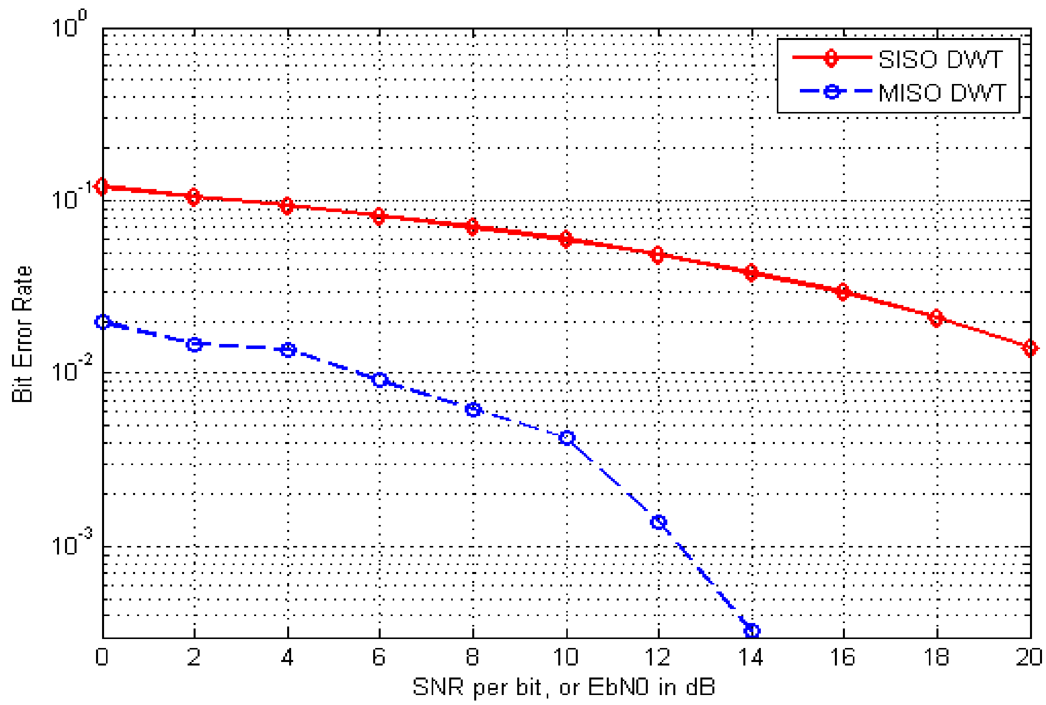

Figure 3. MISO diversity with DWT-OFDM.

The simulation parameters are given Table 2. The wavelet family was dB8, and the modulation scheme was QAM.

Table 2. Simulation parameters for SISO and MISO.

Simulation Parameters	MISO DWT	SISO DWT
Modulation Scheme	QAM 16	QAM 16
DWT family	dB8	dB8
Type of channel	AWGN	AWGN
Number of antennas	2 × 1	1 × 1
SNR range	[0:20]	[0:20]

4.3. SISO and MIMO

According to the aforementioned findings, transmit diversity improved performance, and receive diversity improved performance compared to an SISO channel without any diversity. Therefore, we implemented transmit and receive diversity at the transmitter and receiver, respectively, to increase the system's performance. Figure 4 displays the effectiveness of the wavelet-based channel diversity strategy for SISO and MIMO in terms of BER. At the same BER, the SNR value was 4 dB at 10^{-2} for the MIMO DWT and 20 dB for the SISO DWT. This performance gain difference was 16 dB because the antenna diversity with a two-element ULA with half-length spacing was applied at both the transmitter and receiver. The two-element ULA with half-length spacing was only considered because having less complex wavelet transforms leads to more complexity in the model at both the transmitter and receiver sides during the construction and reconstruction of data processing, as mentioned in Section 3.2. The MIMO DWT had an SNR value of 11 dB at 10^{-3}, which was much better than that of the SISO DWT. The simulation parameters, for which the QAM modulation scheme was used and the dB8 wavelet family was considered, are given Table 3.

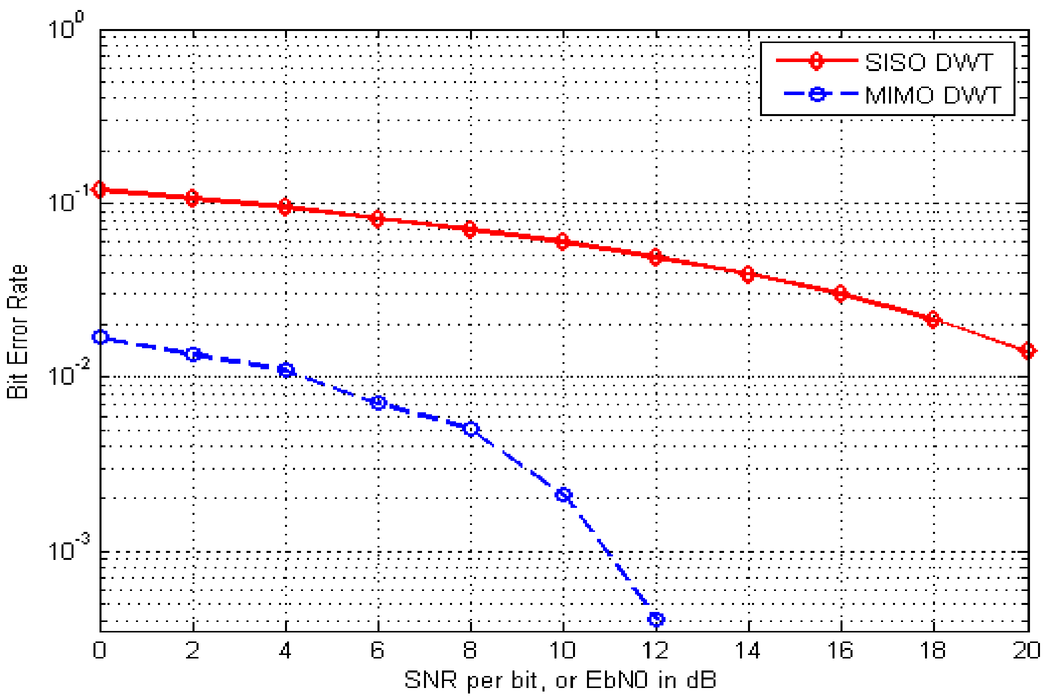

Figure 4. MIMO diversity with DWT-OFDM.

Table 3. Simulation parameters for SISO and MIMO.

Simulation Parameters	MIMO DWT	SISO DWT
Modulation Scheme	QAM 16	QAM 16
DWT family	dB8	dB8
Type of channel	AWGN	AWGN
Number of antennas	2 × 2	1 × 1
SNR range	[0:20]	[0:20]

4.4. Comparison of Different Wavelet Transforms for MIMO DWT

Figure 5 shows the performance results in terms of BER for different wavelet transforms. The wavelet families used were dB8, Haar and Bior 3.5, and the modulation scheme was QAM modulation. When the performance of dB8 was compared with that of Haar and Bior 3.5, the performance of Haar was found to be better in terms of SNR, with an increase of 2 dB, and in terms of BER for the MIMO DWT system in millimeter wave communication systems. The values of SNR at 10^{-3} were 10 dB and 12 dB for Haar and dB8, respectively. Hence, the performance of dB8 family was much better than that of the Bior family.

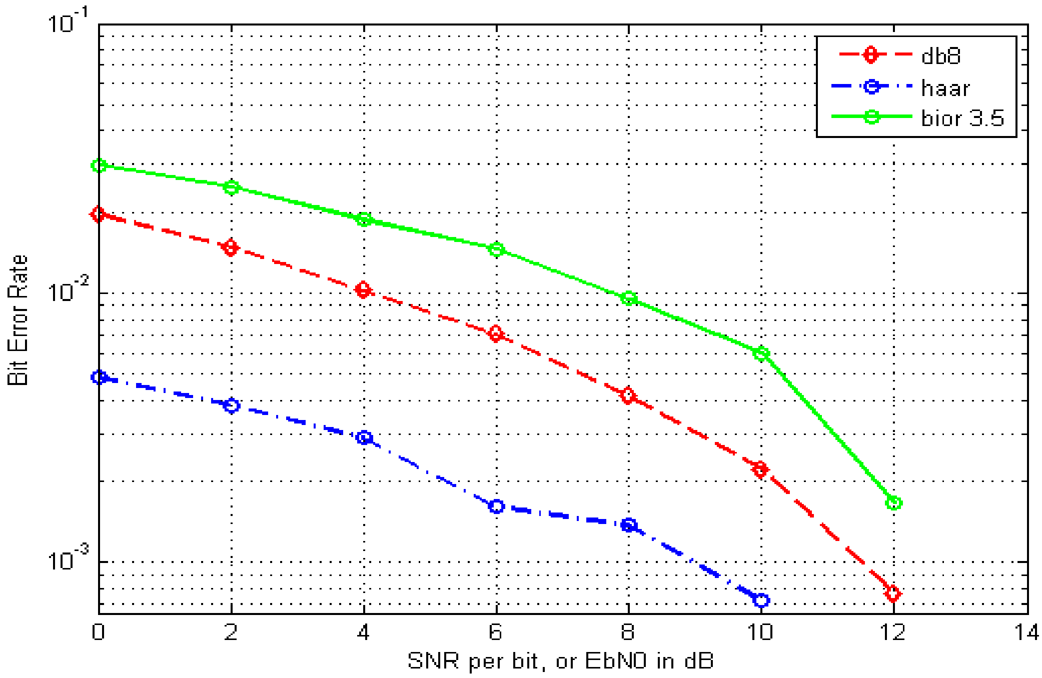

Figure 5. Comparison of different wavelet transforms.

The simulation performance in terms of BER for the MIMO DWT system was analyzed with different wavelets; the parameters are listed in Table 4.

Table 4. Parameters for different wavelets.

Simulation Parameters	MIMO DWT
Modulation Scheme	QAM 16
DWT family	Haar, dB8, Bior 3.5
Type of channel	AWGN
Number of antennas	2 × 2
SNR range	[0:20]

4.5. Comparison of Present Results

4.5.1. Proposed Results with Analytical Method

Figure 6 shows a comparisons of the outcomes of the suggested simulation with those analytically obtained using BER Equation (12). The graph demonstrates that the BER values for the SNR range of 6–8 dB was essentially the same as the simulation findings, with very little variance between them. This means that our proposed simulation results were very close to the analytical results. The accuracy of simulated and proposed results was very close at the median range of SNR (from 6 to 8 dB) compared to highest and lowest values of SNR. The BER values of the simulation findings slightly differed from the analytical results for SNR ranges of 2–4 dB and 8–12 dB. In order to calculate the average BER for the simulation results given that the data were generated at random, the suggested MIMO diversity technique with wavelet transform was iterated a number of times.

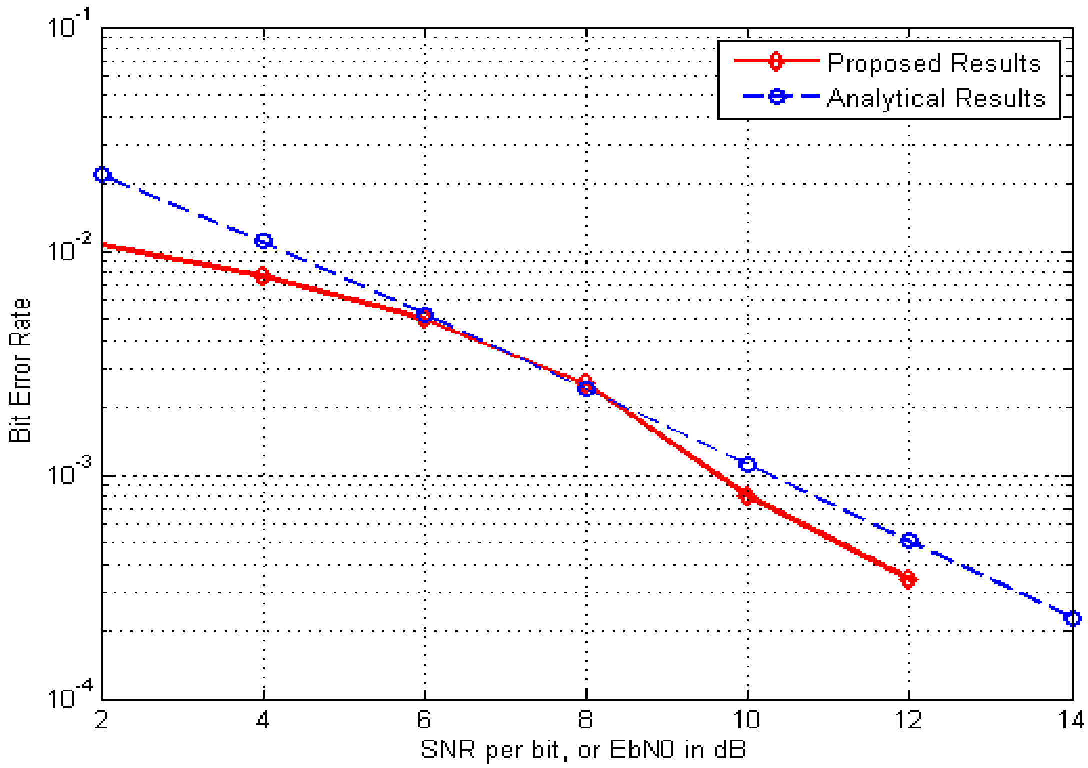

Figure 6. Comparison of results.

Table 5 lists the estimated average BER values, as well as the BER values derived from the BER Equation (12). The table demonstrates that there was only a 0.001 difference between the BER values for the SNR range of 6–8 dB. For the SNR ranges of both 2–6 dB and 8–12 dB, the analytical BER values were higher than the simulated BER values. When the two results were contrasted, however, the BER values revealed less discrepancy. As a result, there was good agreement between the proposed simulation findings and the analytical results.

Table 5. Validation of BER values.

SNR	Analytical BER Value	Average BER (Simulation)
2	21.84×10^{-3}	10.69×10^{-3}
4	11.04×10^{-3}	7.70×10^{-3}
6	5.22×10^{-3}	4.97×10^{-3}
8	2.42×10^{-3}	2.54×10^{-3}
10	1.11×10^{-3}	0.79×10^{-3}
12	0.50×10^{-3}	0.34×10^{-3}

4.5.2. Proposed Results with Existing Work

In the work of Vani and Bargade [30], the BER value at 10^{-3} was 12 dB for the Haar wavelet family for the 2×2 MIMO diversity technique using 16 QAM modulation, whereas our proposed technique using a two-element ULA with half-length spacing had an SNR value of 9 dB for the same BER, wavelet family, and modulation scheme. Therefore, our technique showed an improvement of 3 dB diversity gain. Similarly, for the Daubechie and Bior wavelet families, our work demonstrated a significant improvement of 10 dB gain using 16 QAM modulation at $10^{-1.6}$ and $10^{-1.5}$, respectively. Furthermore, in the work of Srivastava and Chourasia, [31] for the Daubechie wavelet family, the BER value at 10^{-2} was 14 dB using 16 QAM modulation, whereas our proposed technique using two-element ULA with half-length spacing had an SNR value of 4 dB for the same BER, wavelet family, and modulation scheme. Therefore, our technique showed an improvement of 10 dB diversity gain.

At 10^{-2} of BER, our technique led to the same SNR value as that of Gupta and Thakur, [32] using a 16 QAM modulation scheme. However, the wavelet families were different. They used a DWT with a discrete cosine transform (DCT). In addition at 10^{-3} of BER, the work of [32] showed a better improvement of diversity gain compared to our results due to fact that those researchers used a DCT in addition to a DWT while we used the Daubechie wavelet family. Therefore, based on the comparisons shown in Table 6, our diversity technique led to a significant improvement in terms of BER.

Table 6. Comparison of presented results with existing work.

Reference	BER	SNR	Wavelet	Modulation
Vani and Bigrade, [30]	10^{-3}	12 dB	Haar	16 QAM
	$10^{-1.6}$	12 dB	Db2	16 QAM
	$10^{-1.5}$	12 dB	Bior	16 QAM
Srivastava and Chourasia, [31]	10^{-2}	14 dB	Db2	16 QAM
Gupta and Thakur, [32]	10^{-3}	6 dB	DWT DCT	16 QAM
	10^{-2}	3.5 dB	DWT DCT	16 QAM
Present work	10^{-3}	9 dB	Haar	16 QAM
	10^{-2}	4 dB	Db8	16 QAM

5. Conclusions

Antenna diversity techniques with wavelet transform were developed and analyzed by using two-element ULA and half-length spacing. The performance of the SIMO DWT and the MISO DWT was strong, with a gain of 2 dB compared with the SISO DWT. However, the performance of the MIMO DWT was much better than that of the SIMO and MISO DWTs, with a gain of 2 dB. We compared the MIMO diversity technique with different wavelets and found that the simplest Haar wavelet transform was better in terms of performance, with a gain of 2 dB. The numerical simulation results were in good agreement with the analytical results. For future study, the MIMO diversity technique with a four-element ULA can be investigated.

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References

1. Parveen, N.; Abdullah, K.; Badron, K.; Diyana, F.; Rahman, A.; Morshidi, A. Bin Generation and Analysis of 5G Downlink Signal. *J. Adv. Res. Appl. Sci. Eng. Technol.* **2022**, *1*, 23–30.
2. Harkat, H.; Monteiro, P.; Gameiro, A.; Guiomar, F.; Farhana Thariq Ahmed, H. A Survey on MIMO-OFDM Systems: Review of Recent Trends. *Signals* **2022**, *3*, 359–395. [CrossRef]
3. Antenna, F.; Hfaa, A.; Alghamdi, S.; Alassery, F. A Novel Approach of Design and Analysis of a Hexagonal Wireless Communication. *Energies* **2021**, *14*, 6204.
4. Kirik, M.; Hamamreh, J.M. Interference Signal Superposition-aided MIMO with Antenna Number Modulation and Adaptive Antenna Selection for Achieving Perfect Secrecy. *RS Open J. Innov. Commun. Technol.* **2021**, *2*, 1–11. [CrossRef]
5. Karatepe, S.; Kirik, M.; Hamamreh, J.M. Novel Nonorthogonal Multi-access Method for Multi-user MIMO with Antenna Number Modulation. *RS Open J. Innov. Commun. Technol.* **2021**, *2*, 1–5. [CrossRef]
6. Ahmad, M.; Shin, S.Y. Massive MIMO NOMA with wavelet pulse shaping to minimize undesired channel interference. *ICT Express* **2022**. [CrossRef]
7. Majdoubi, A.; Essaaidi, M. The Estimation of DOA in Smart Antenna Systems. *Int. J. Innov. Technol. Explor. Eng.* **2012**, *1*, 132–134.
8. Habib, U.; Aighobahi, A.E.; Nair, M.; Zhu, H.; Quinlan, T.; Walker, S.D.; Nathan, J. Performance Improvement for OFDM-RoF Transported 60 GHz System using Spatial Diversity and Multiplexing. In Proceedings of the The 10th International Workshop on Evolutional Technologies & Ecosystems for 5G and Beyond (WDN-5G ICC2017) Performance, Paris, France, 21–25 May 2017; pp. 1–6.
9. Sethi, W.T.; Vettikalladi, H.; Minhas, B.K.; Alkanhal, M.A. High gain and wide-band aperture-coupled microstrip patch antenna with mounted horn integrated on FR4 for 60 Ghz communication systems. In Proceedings of the 2013 IEEE Symposium on Wireless Technology & Applications (ISWTA), Kuching, Malaysia, 22–25 September 2013; pp. 359–362. [CrossRef]
10. Talbi, L.; Lebel, J. Broadband 60 GHz sounder for propagation channel measurements over short/medium distances. *IEEE Trans. Instrum. Meas.* **2014**, *63*, 343–351. [CrossRef]
11. Haneda, K.; Gustafson, C.; Wyne, S. 60 GHz spatial radio transmission: Multiplexing or beamforming? *IEEE Trans. Antennas Propag.* **2013**, *61*, 5735–5743. [CrossRef]
12. Daniels, R.; Heath, R., Jr. 60 GHz wireless communications: Emerging requirements and design recommendations. *IEEE Veh. Technol. Mag.* **2007**, *2*, 41–50. [CrossRef]
13. Abdullah, K.; Hussain, Z.M. Studies on DWT-OFDM and FFT-OFDM Systems. In Proceedings of the International Conference on Communication, Computer And Power, Muscat, Oman, 15–18 February 2009; pp. 15–18.
14. Chafii, M.; Harbi, Y.J.; Burr, A.G. Wavelet-OFDM vs. OFDM: Performance Comparison. In Proceedings of the 23 rd Internatonal Conference on Telecommunications ICT, Thessaloniki, Greece, 16–18 May 2016; pp. 1–5.
15. Manure, S.S.; Raj, C.P.P.; Naik, U.L. Design and performance analysis of DWT/FFT based OFDM systems. In Proceedings of the 3rd International Conference on Advances in Recent Technologies in Communication and Computing (ARTCom 2011), Bangalore, India, 14–15 November 2011; pp. 167–170. [CrossRef]
16. Jhingan, A.; Kansal, L. Performance Analysis of FFT-OFDM and DWT-OFDM over AWGN Channel under the Effect of CFO. *Indian J. Sci. Technol.* **2016**, *9*, 1–16. [CrossRef]
17. Jhingan, A.; Kansal, L. Performance Evaluation for Wavelet based OFDM System effected by CFO over Rayleigh Channel. *Indian J. Sci. Technol.* **2016**, *9*, 1–6. [CrossRef]
18. Rao, G.S.; Kumar, T.J.S. Simulation of Models and BER Performances of DWT-OFDM versus DAUBECHIES-OFDM G. *Int. J. Innov. Res. Dev.* **2011**, *3*, 260–264. [CrossRef]
19. Singh, S.; Kumar, P.; Prasad, S. Improvement of BER in Wavelet Transform-based OFDM System with Kalman Filter. *J. Commun. Eng. Syst.* **2016**, *4*, 2–8.
20. Bouhlel, A.; Sakly, A.; Mansouri, N. Performance Comparison of DWT Based MIMO OFDM and FFT Based MIMO OFDM. *Procedia Comput. Sci.* **2015**, *73*, 266–273. [CrossRef]
21. Meenakshi, D.; Prabha, S.; Raajan, N.R. Compare the performance analysis for FFT based MIMO-OFDM with DWT based MIMO-OFDM. In Proceedings of the 2013 IEEE International Conference ON Emerging Trends in Computing, Communication and Nanotechnology (ICECCN), Tirunelveli, India, 25–26 March 2013; pp. 441–445. [CrossRef]
22. Ranjitha, P.; Jayabhavani, G.N. Performance Analysis of Ber Using Dwt Based Mimo-Ofdm System. *Int. J. Adv. Eng. Glob. Technol.* **2015**. Available online: https://www.semanticscholar.org/paper/PERFORMANCE-ANALYSIS-OF-BER-USING-DWT-BASED-SYSTEM-Ranjitha-Jayabhavani/003093fe5f6d0493ac2bc9dc742c3a24c70cf07c#citing-papers (accessed on 8 August 2022).
23. Meenakshi, D.; Prabha, S.; Raajan, N.R. Evaluation of BER for various fading channel in DWT based MIMO-OFDM system. *Int. J. Eng. Technol.* **2013**, *5*, 1069–1075.
24. Parveen, N.; Abdullah, K.; Islam, R.; Boby, R.I. Diversity Technique Using Discrete Wavelet Transform In OFDM System. *Int. J. Eng. Adv. Technol.* **2019**, *8*, 284–287.

25. Parveen, N.; Abdullah, K.; Islam, R.; Boby, R.I. Performance of MIMO DWT for Millimeter Wave Communication System. In Proceedings of the 2019 IEEE 14th Malaysia International Conference on Communication (MICC), Selangor, Malaysia, 2–4 December 2019; pp. 2–4.
26. Baig, S.; Fazal-ur-Rehman; Mughal, M.J. Performance comparison of DFT, discrete wavelet packet and wavelet transforms, in an OFDM transceiver for multipath fading channel. In Proceedings of the Pakistan Section Multitopic Conference, INMIC, Karachi, Pakistan, 24–25 December 2005.
27. MATLAB Inc. *MATLAB R2017a:Theory Guidance*; MATLAB Inc.: Asheboro, NC, USA, 2017.
28. Raouf, H.; Yousef, H.; Ghonem, A. An Analytical Comparison between Applying FFT and DWT in WiMAX Systems. *Int. J. Comput. Sci. Issues* **2014**, *11*, 18–26.
29. Zhu, J. Optimal Design of Uniform Circular Antenna Array in mmWave LOS MIMO Channel. *IEEE Access* **2018**, *6*, 61022–61029. [CrossRef]
30. Vani, A.; Bargade, P.S. Improvement of ber for mimo-ofdm system using wavelet transform. *Int. J. Innov. Technol. Explor. Eng.* **2019**, *8*, 204–207.
31. Srivastava, S.; Chourasia, B. Analysis of Ber Performance of Ofdm System Using Different Modulation Methods. *Int. J. Sci. Res. Eng. Trends* **2021**, *7*, 6–9.
32. Gupta, V.; Thakur, R. PAPR And BER Performance of Filter Design For Mimo-Ofdm Systems with Multiple Waveform Constraints. *Int. J. Recent Trends Technol. Electron. Commun. Eng.* **2019**, *1*, 57–64.