Design and implementation of programmable MIMO-FFT-OFDM and MIMO-DWT-OFDM/MIMO-FBMC on an Embedded Platform Architecture for 5G applications

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Abstract: Service providers in 4G wireless communication networks are constantly challenged to accommodate more customers within a limited allotted capacity. OFDM (Orthogonal Frequency Division Multiplexing) is used to boost the data rate of a wireless medium while reducing interference. It is important to analyse the performance of the FFT- and DWT-OFDM by using different methods and algorithms. In this paper FFT and DWT is employed with different algorithms such as Cooley-Tukey, Prime factor, Haar and Daubechies. These algorithms have been modeled and analysed for the designed software model. A Comparative analysis has been carried out by considering SNR (Signal-to-Noise Ratio) and BER (Bit Error Rate) values for QAM modulation. MATLAB simulation showed that DWT-based OFDM system performed much better than the FFT-based OFDM systems on AWGN channel. 5G technology involves communication engineering and embedded system engineering to enhance the required data rate for different applications. The proposed system implementation with the 5G MIMO-OFDM on Zynq UltraScale provides a data rate within a range of 10 Gbps to 50 Gbps for the different order of the combinations of FFT/IFFT or DWT/IDWT and QAM. The different orders of the combinations were achieved through programmability and reconfigurability. The performance of the DWT-OFDM is more complex and computationally intensive than that of FFT-OFDM in hardware. In future wok the proposed system could be improved so as to become a multi-user MIMO(MU-MIMO).

Keywords: FFT/IFFT, DWT/IDWT, 5G/4G, MIMO-OFDM, Embedded Systems, Zynq-UltraScale.

1. Introduction

Fifth Generation (5G) communication systems comprise communication systems that can give a higher data rate, increasing network capacity with high-speed data and throughput with low latency-based applications. 5G has aggressive performance requirements for a variety of applications, including IoT Cloud applications and automobile networks, which rely heavily on orthogonal frequency division multiplexing (OFDM) and Multiple-Input Multiple-Output (MIMO) systems based on physical layer technologies such as transceivers and smart antennas for a data-rate based on application targets. The key aims of 5G technology are to execute high-speed applications, as well as to provide reliability and security for system development and deployment (Rashid & Rasak, 2019; European Commission, 2021; IEEE, 2017).

OFDM is a multi-carrier technology that modulates data into sets of orthogonal frequencies using FFTs. The frequency domain data is translated into the time domain by an Inverse (IFFT) at the transmitter, and the received signals are converted back into the frequency domain by a FFT at the receiver. The construction of an IFFT is identical to that of a FFT, the distinction being that the twiddle factors in one of them are complex conjugates of the other. Similarly, DWT is an important component of OFDM symbol modulation. The transmitter segment will represent inverse DWT, whereas the reception segment will model DWT. Both forward and reverse transformations are primarily include of low-pass and high-pass filters with approximate and detail coefficients. Forward and reverse transform coefficient values vary. The perfect reconstruction property is satisfied by modelling these factors with the properties of DWT realise an FBMC (Bouhlel et al., 2015; Singh & Shukla, 2019; Singh & Yadav, 2020).

The structure of this paper is as follows. Section 2 presents the related works and a literature review. Section 3 sets forth design and implementation of the model-based software and embedded system. Section 4 discusses the obtained simulation results and testing including the results for

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model-based and embedded systems including the respective data rates. Section 5 presents a comparison of the values of data rates and execution time for the MIMO-OFDM system, which were obtained in this work and in other works from the existing literature. Section 6 includes the conclusions of this paper and future work proposal.

2. Literature review and related work

Most of the Orthogonal Frequency Division Multiplexing (OFDM) systems are software-defined Radio (SDR) based systems which need to have a better prototype for real-time applications. The high-performance Digital Signal Processing (DSP) systems are significant because of its dedicated signal processing computation resources per the needs of proper computing elements for SDR (Ghosh et al., 2022). Ganesh et al. (2015) had implemented the OFDM stating its significance for the 5G data rates but the authors didn't mention any data rate calculations. The Orthogonal Frequency Division Multiple Access (OFDMA) provides an uplink and downlink disparity for the modern Long-Term Evolution (LTE) architecture through hardware design and implementation (Venkatraman et al., 2019). In modern communication systems Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) is commonly utilised to deliver high data transmission speeds and spectrum efficiency (Basavaraj & Sujatha, 2021). MIMO technology, OFDM-based transmission, modulation, and channel coding were emphasised as common technologies to boost system capacity and transmission dependability. Fast Fourier Transform (FFT) is the main component of the sub-channel and data rate increment (Dali et al., 2017).

When compared to FFT-based OFDM systems, the DWT-OFDM system is more resistant to multipath fading and interference as it was simulated with 5x5 wavelet-based MIMO-OFDM, but the author has no evidence of data rates (Singh & Shukla, 2019). Bouhlel et al. (2015) presented MIMO and OFDM as the two technologies for providing spectral efficiency and higher data rates. The authors presented a comparative analysis of FFT MIMO-OFDM and DWT-MIMO-OFDM. The study was performed with QAM of 4, 16 and 64 and detection techniques zero forcing (ZF), Maximum likelihood (ML) and minimum mean square error (MMSE). The results showed that there is no requirement for CP due to the overlapping properties of DWT. Also, the BER of the system has improved, hence there is no mention of data rate (Bouhlel et al., 2015; Murali et al., 2018; Vamsidhar et al., 2017). Randrianandrasana et al. (2022) had implemented a RADAR MIMO for improving doppler effect, thereby improving the BER. The Filter Bank based MultiCarrier (FBMC) is used in 5G, the Lift Wavelet Transform (LWT) is used for the formation of LWT-FWMC along with DFT and DCT and compared with PAPR and BER for each method. The LWT features a lower PAPR compared with other techniques and a good performance, but there is no mention of data rates. The MIMO and OFDM are of great interest for improvement of 5G data rates. Kumar & Khera (2022) in their paper proposed a new partial transmit sequence (PTS) technique with discrete wavelet transform (DWT) and discrete cosine transform (DCT) with 2x2 antenna with a reduced BER and a better PAPR. Asif et al. (2017) proposed a DWT-based MIMO-OFDM without guard time insertion limitations since signal distortion when passing over the channel does not influence orthogonality, which is maintained using the PRQMF bank. Wavelets are more attractive since they obtain a better SNR than traditional FFT-OFDM systems due to signal energy confinement in the main lobe and suppressed side lobes. Also, the cyclic prefix in FFT-OFDM has the disadvantage of reducing the spectral containment of the channel. In Simulation FBMC outstands over OFDM in simulation (Adarsh et al., 2023; Ramakrishnan et al., 2021; Vaigandla & Benita, 2022). But on other hand the implementation complexity is higher for embedded systems, (Al-Haddad & Ziboon, 2021; Gomes et al., 2018).

The use of MIMO at transmitter and receiver allows high data rate transfers and an enhanced link quality. Hence, the aim of high data rate MIMO communication systems has gained a greater importance because MIMO provide diversity by using many paths. Numerous antennas are used in MIMO to broadcast numerous parallel signals (from the transmitter), this signal passes through various environments like buildings, trees etc. and reaches the receiver. At the receiving end, MIMO uses algorithms to sort the various signals and construct a signal that will be transmitted.

By using these multiple parallel signals loss of signal can be overcome (Dali et al., 2017; Murali et al., 2018; Vamsidhar et al., 2017). Field Programmable Gate Array (FPGA) based processing and its reconfigurability are gaining popularity due to its architecture with Processing System (PS) and Programmable Logic (PL) (Berlee, 2021; Guo, 2015). The Zynq platform is planned to provide a dependable foundation for ongoing experimentation and innovation by wireless communication professionals (Handagala 2020; Parvez, et al., 2018; AMD Xilinx, 2023).

3. Proposed design and implementation

The most significant advancement of 5G technology is the transmission speed with low latency, which becomes possible due to advancements in embedded architecture design and development, which will provide a higher computation capability with multi-core processors and programmable logics with high-end FPGA providing reconfigurability and programmability. Because these enormous devices may be connected to servers, cloud computing platforms, and device-to- device communications for the applications, embedded architecture and 5G and its applications enable an improved connection.

3.1. Model-based design and implementation in software

The design and implementation of FFT-OFDM are illustrated in Figure 1. Cooley-Tukey radix-2 and radix-4 FFT/IFFT algorithms are considered. To begin implementation, various considerations are made, and the data is initially separated into frames. Frame divisions are produced by dividing the total length of data by 120, which yields the number of frames. Each frame contains input data, encoded-decoded data, modulated-demodulated data, Fast Fourier Transform (FFT) and Inverse FFT operations, and cyclic prefix addition and removal. All the blocks are a crucial components. The FFT method is used to compare the performance of the Cooley-Tukey and that of the Prime factor algorithms (Proakis & Manolakis, 2007). The implementation is as follows:

- The input data is analysed, and the length of the input is calculated; the input data is then transformed into binary form;
- The binary data is separated into frames; after the frames are collected, a 1/3 rate convolution encoder is used;
- The QAM modulation converts serial data into parallel data, performs IFFT operation with given N data points FFT that is 128 which is equal to 128 subcarriers, and cyclic prefix is added;
- An Adaptive White Gaussian Noise channel is provided for the removal of cyclic prefix and FFT operation followed by QAM demodulation;
- The Performance of FFT_OFDM is compared based on Bit Error Rate for input data and demodulation output data.

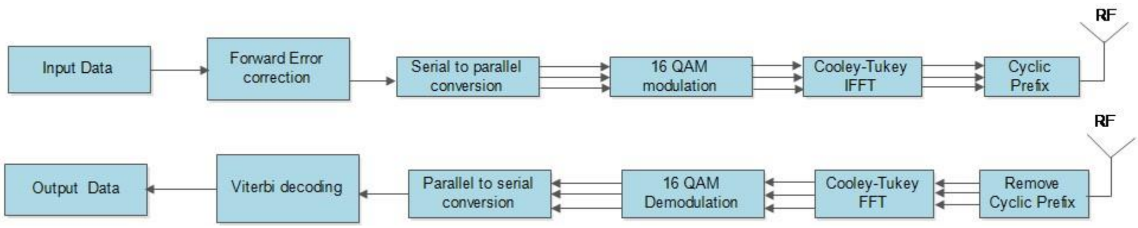

Figure 1. Block Diagram of FFT-OFDM

The implementation of each subblock, as well as that of the DWT algorithm, is the second part of the work of the OFDM trans receiver, as it is illustrated in Figure 2. The wavelet type used for the DWT/IDWT algorithm is Haar and Daubechies. To begin the implementation, various considerations are made, and the data is initially separated into frames. Frame divisions are produced by dividing the total length of data by 120, which yields the number of frames. Each frame contains input data, encoded-decoded data, modulated-demodulated data, DWT and IDWT operations, and cyclic prefix addition and removal. The cyclic prefix is optional because DWT provides the orthogonality and filter bank needed to deliver FBMC features. Furthermore, when done in real-time, DWT without a cyclic prefix can save processing power.

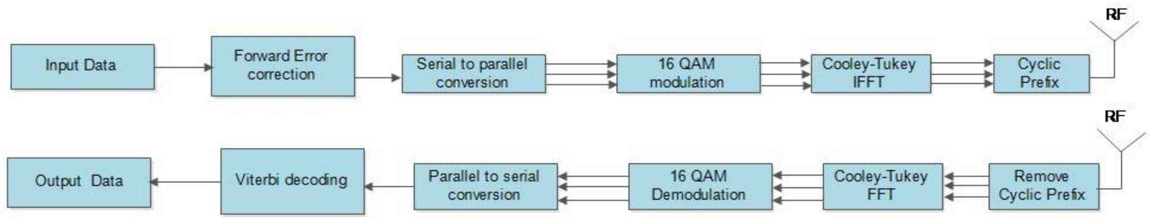

Figure 2. Block Diagram of DWT-OFDM

The implementation is described below:

- The input data is analyzed, and the length of the input is determined; the input data is then transformed into binary data;
- The binary form data is separated into frames; after the frames are collected, a 1/3 rate convolution encoder is applied;
- QAM modulation turns serial data into parallel data, performs IDWT operations with a specified N data points DWT of 128 (equivalent to 128 subcarriers), and adds a cyclic prefix;
- An Adaptive White Gaussian Noise channel is provided, which was subsequently used for the elimination of cyclic prefix and DWT operation, followed by QAM demodulation;
- The performance of DWT-OFDM is compared based on Bit Error Rate for input data and the demodulation output data;
- If you wish to use it as a FBMC, you don't need the cyclic prefix, and the DWT will provide orthogonality and a filter bank.

3.2. Embedded system design and implementation

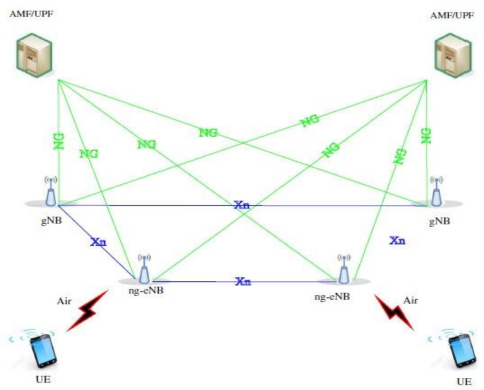

Figure 3. 5G Architecture for 5G Applications (Mishra et al., 2021)

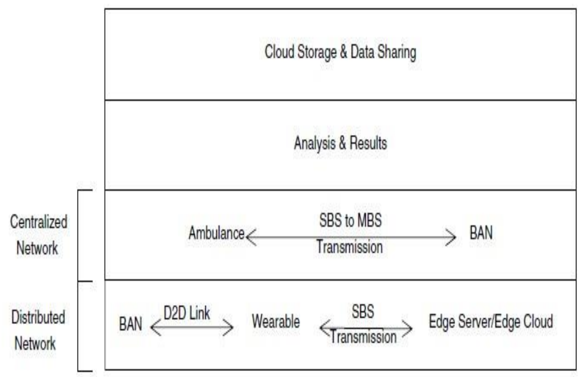

Figure 4. Centralized and Distributed 5G Networks of 5G (Mishra et al., 2021)

The most significant advancement of 5G technology is the transmission speed with low latency, which become possible due to advancements in embedded architecture design and development. These developments provide a higher computation capability with multi-core processors and programmable logics with high-end FPGA providing reconfigurability and programmability. Figure 3 depicts the 5G Architecture from the perspective of communication engineering. The centralized and distributed 5G networks are depicted in Figure 4. Figure 5 depicts a 4x4 MIMO-OFDM Communication System that is programmed as MIMO-FFT- and DWT-OFDM/FBMC.

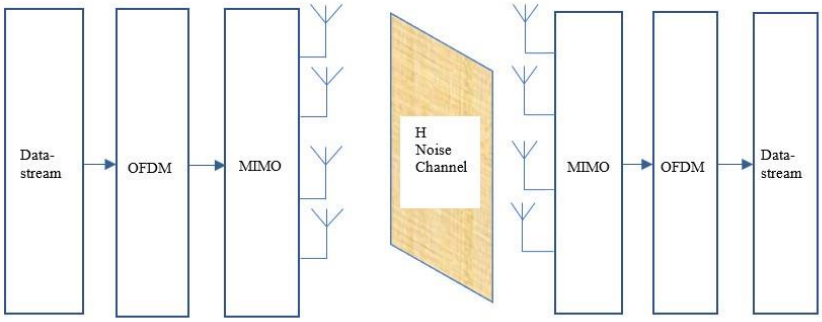

Figure 5. Block Diagram of a 4 x 4 MIMO-OFDM Communication System

A 4x4 MIMO-OFDM system using Space-Time Block Code (STBC) as MIMO pre-encoder and decoder with OFDM with higher-order Quadrature Amplitude Modulation (QAM), higher-order FFT, and a cyclic prefix is designed. The data rate supplying blocks, together with the traditional encoder at the transmitter and Viterbi decoder at the receiver, include a higher-order QAM and FFT or DWT-based orthogonality considerations. The OFDM modulated symbol is processed using the Alamouti precoding technique to deliver the information signal utilizing the four-antenna. Estimates of the transmitted symbols are produced at the receiver by using recombination procedures. These symbols are then demodulated to output the bit stream of 0s' and 1s'.

Reconfigurable computing and its platforms are playing an important role in the design of embedded systems, including hardware and software for system architecture, as well as improving system performance in terms of data rate and throughput. A proper component analysis is required to accomplish the desired functionality of the OFDM. The FEC encoder, modulation method, serial to parallel converter, IFFT with the Cooley-Tukey radix-2 are considered for the FFT/IFFT algorithm all of them being part of the OFDM system at the transmitter. When DWT-based OFDM is employed, a Haar or db4 is used, the parallel to serial converter and the addition of Cyclic Prefix (CP) at the transmitter. The receiver implements the reverse blocks. The QAM and FFT/IFFT are both computationally demanding.

The Zynq UltraScale supports the Advanced eXtensible Interface (AXI) bus to interface with the programmable Intellectual property (IP), which includes Viterbi decoders, programmable QAM for modulation and demodulation, and MIMO encoders and decoders on the device's programmable logic and communicating with the PS main processor, which is an ARM cortex-A53 type. The PS main processor is computing the blocks through parallel to serial and serial to parallel computations, other digital signal processing, and control software. A Mali-400 Graphics processor is computing the higher order of the FFT/IFFT and DWT/IDWT operation through its provided libraries for the Zynq UltraScale devices. The device can be operated in the frequency range of 750 to 1600 MHz with regards to the application requirement so as to enable the higher data rate. The computation complexity of the DWT is higher than that of FFT.

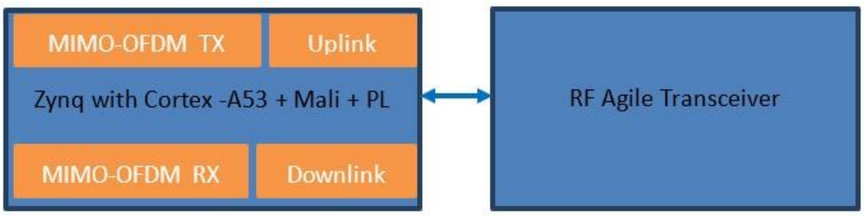

Figure 6. 4x4 MIMO-OFDM Implementation with Zynq with Cortex-A53, Mali-400 GPU Processor, PL, and RF Agile Transceiver Block

Figure 6 depicts the embedded architecture of the 5G eNodeB based on the Zynq Cortex A-53 with Mali-400 processor and PL. For a high performance and 4G and 5G applications, the implementation is conducted using the RF agile transreceiver for Radio Frequency (RF) processing utilizing the AD936x with RF synchronized 4x4 Dual AD9361 transceiver (AD_FMCOMMS5-EBZ).

4. The analysis of simulation results

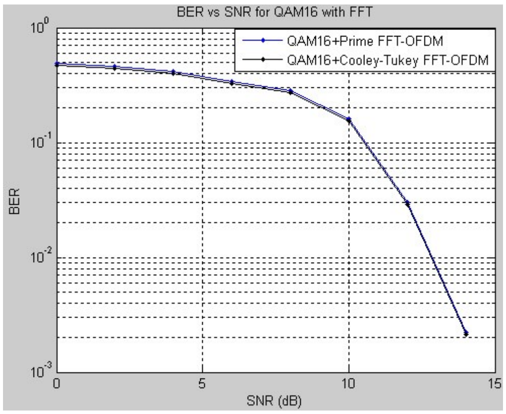

Figure 7. BER vs. SNR for 16-QAM with FFT for FFT-OFDM

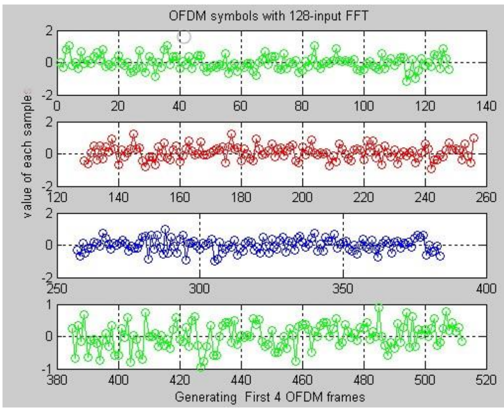

Figure 8. OFDM Symbols with 128-input FFT

The Cooley-Tukey radix-2 FFT algorithm is created, studied, and tested with the proposed OFDM transceiver. The IFFT and 16-QAM modulation blocks are added to the transmitter block, while the FFT blocks are added to the receiver block. The BER versus SNR plots depict the bit error rate for the full OFDM transceiver architecture. Figure 7 shows a SNR against a BER plot in which the number of bit error rates decreases as the SNR value increases. The quantity of bit errors is practically 0 bits at 14 dB, allowing for a perfect reconstruction. As a consequence, this graph compares the total bit error rate for the FFT Cooley-Tukey algorithm implementation with that of the prime factor method implementation with 16-QAM modulation. For both FFT techniques, the BER vs. SNR is nearly identical. Figure 8 depicts the creation of OFDM symbols using frames. Each frame has 120 bits in addition to a cyclic prefix. OFDM transceiver output is obtained by using 128-input FFT. Figure 9 depicts the grayscale image of 128 input FFT and IFFT output.

In this work, system design begins with obtaining picture input data. The images can be binary, greyscale, or RGB, the analysed picture is a greyscale image (52x52), which is then converted to a binary value and sent to the proposed OFDM transreceiver. After decoding, the bit error rate is applied and the SNR vs BER for the created the FFT-OFDM transreceiver are displayed.

Figure 9. Input-Output Image of OFDM Transreceiver with 128-FFT OFDM

Figure 10 depicts the curve of SNR versus BER. As the SNR value grows, the values of bit error rates decreases, therefore the number of bit errors for the transmission of 10000 bits is 4590, as it can be seen in Figure 7. The number of bit errors is approximately 0 at 14 dB, implying that a flawless reconstruction is accomplished. As a result, the graphic in Figure 10 depicts the implementation of DWT Haar and db2 wavelet transformations with 16-QAM modulation. In the case of Haar wavelets, the number of coefficient is lower since the length of the wavelet series grows as the number of coefficients increases. Figure 10 also depicts the theoretical value of the 16-QAM modulation approach with a constant K value throughout a range of SNR changes in decibels. So wave smoothing is possible, however, wavelets such as the bi-orthogonal one have a lower bit error rate as SNR values decline. Figure 11 depicts the creation of OFDM symbols using frames. Each frame has 120 bits in addition to a cyclic prefix. OFDM transceiver output is obtained by using 128-input DWT.

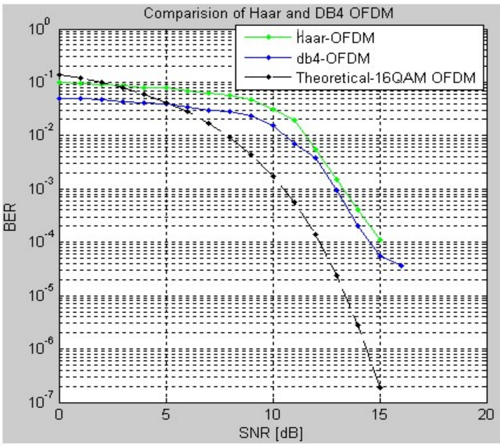

Figure 10. BER vs. SNR for 16-QAM based Haar and db4 OFDM Wavelet with FFT-OFDM

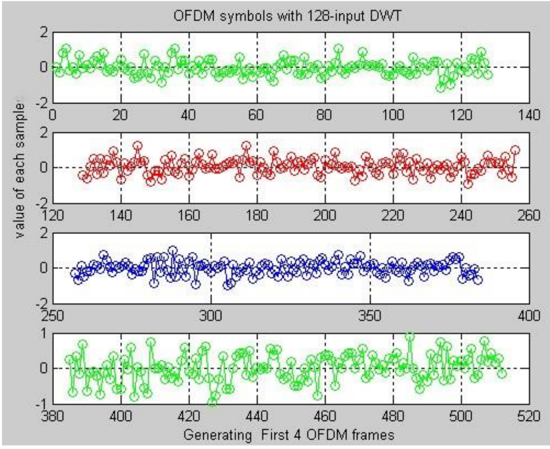

Figure 11. OFDM Symbols with 128-input DWT

Figure 12 depicts the creation of OFDM symbols using frames. Each frame has 120 bits, as well as a cyclic prefix for the Haar DWT OFDM. The original picture is analyzed, and DWT is used to execute the Haar wavelet-based operation and provide detail and approximation coefficients using an inverse Haar wavelet transformation to reconstruct the original image. Similiarly, Figure 13 depicts the creation of OFDM symbols using frames. Each frame has 120 bits, as well as a cyclic prefix for the Daubechies DWT OFDM. The original picture is analyzed, and DWT is used to execute the Daubechies operation and provide detail and approximation coefficients using an inverse Daubechies wavelet transformation to reconstruct the original image.

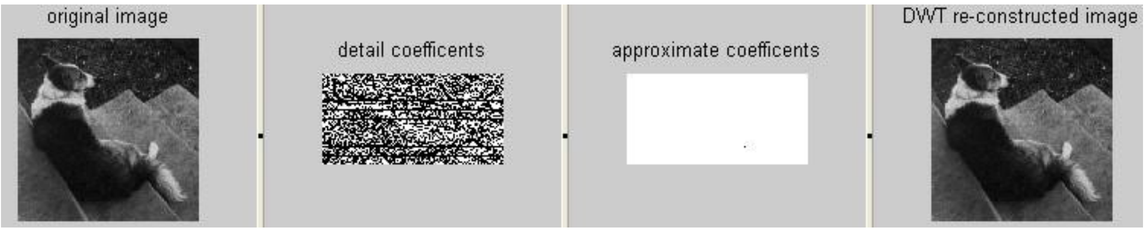

Figure 12. Input-Output Image of OFDM-Transreceiver with 128-DWT Haar OFDM

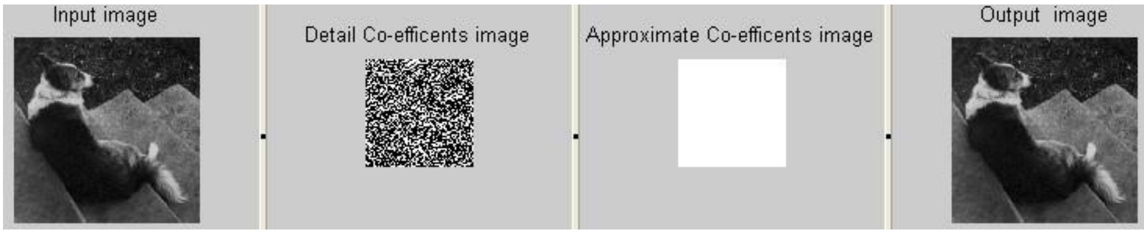

Figure 13. Input-Output Image of OFDM-Transreceiver with 128-DWT Daubechies OFDM

Table 1. Comparison of BER vs SNR for Haar and db4-OFDM Wavelet Transform

SNR (db)	BER of FFT-OFDM	BER of Haar-OFDM	BER of db4-OFDM
0	0.1392	0.0495	0.0989
5	0.0419	0.0380	0.0761
10	0.0018	0.0169	0.0383
15	0.0000	0.0001	0.0003

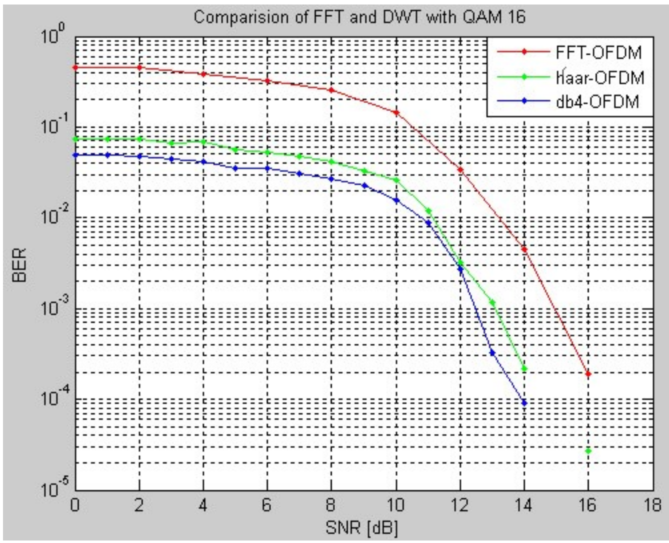

Figure 14. Comparison of FFT and DWT Algorithm with 16-QAM

As it can be seen in Figure 14, the number of bit error is approximately 0 at 14 dB, showing that perfect reconstruction is attainable. As a consequence, this diagram illustrates the use of DWT Haar and db4 wavelet transformation with 16-QAM modulation. The number of coefficients in the Haar series increases as the length of the Daubechies wavelet series increases. As a consequence, the implementation of DWT Haar and db2 wavelet transformations with 16-QAM modulation outperforms FFT approaches, as it can be seen in this graph. The comparison of the BER and SNR values for the Haar and Daubechies wavelets is depicted in Figure 14. As it can be seen, the Daubechies wavelet has a lower BER rate than the Haar wavelet. Table 1 shows the results of a comparison for BER and SNR values using FFT-OFDM and DWT (Haar and Daubechies)-OFDM.

The multiplexing and diversity gains of a MIMO system are investigated using Alamouti precoding method. In various precoding systems, the number of antennas used at the transmitter and receiver defines the diversity gains, and QAM is utilised to modulate symbols. Figure 15 depicts the SNR versus BER graph for 16-QAM with BER decreasing to 10-3 at 15 dB and for 16-QAM paired with MIMO-OFDM with a falling BER to 10-4 at 9 dB SNR. It illustrates the MIMO system's dependability and reduces the bit error rate. The advantage of 16-QAM is its high spectrum efficiency. The results of the implementation of a 4x4 MIMO-OFDM transmitter and receiver on Zynq UltraScale devices using C and Verilog language are further described. Figure 16 depicts the output of the MIMO-OFDM receiver implementation. The OFDM spectrum for the ideal AWGN channel with the following properties is depicted in Figure 17.

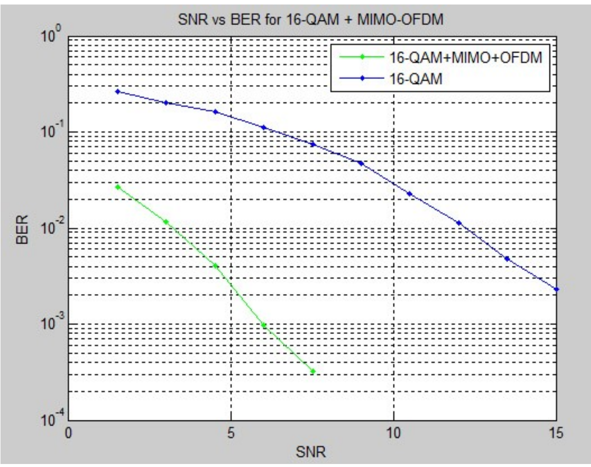

Figure 15. SNR vs. BER for 16-QAM with 4x4 MIMO-OFDM

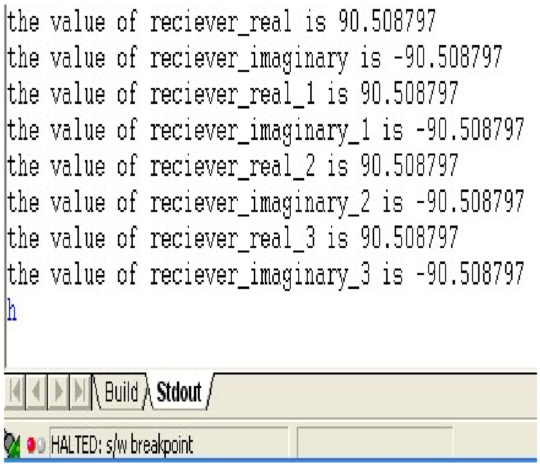

Figure 16. Output of the MIMO-OFDM Receiver

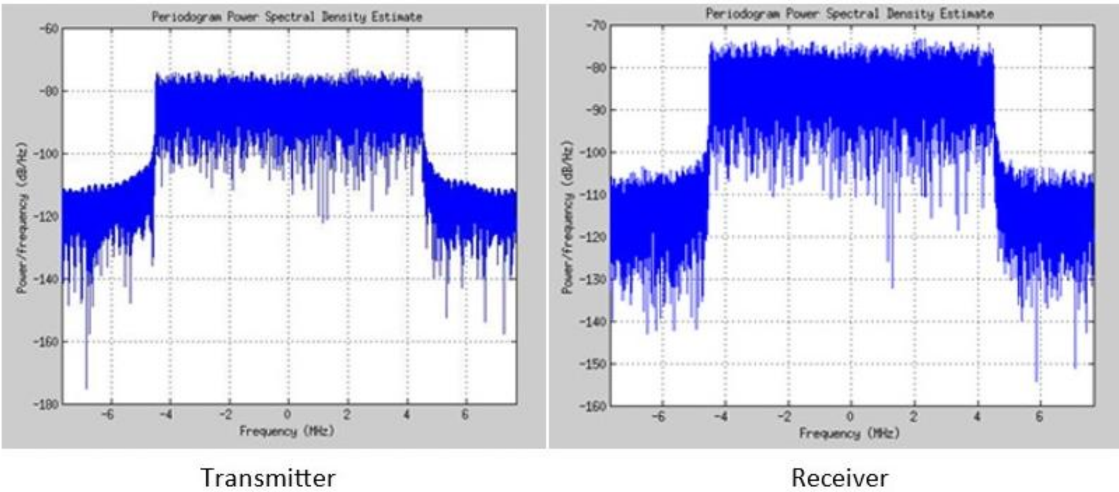

Figure 17. Transmitter and Receiver OFDM Spectrum for the ideal AWGN Channel

4.1. MIMO-OFDM validation and verification

Figure 18 shows the simulations results for colour and bit images transmission between the transmitter and receiver using 16-QAM at 1 dB. The image quality is proper with a SNR of 10 dB. The advantage is the increase of 10 dB.

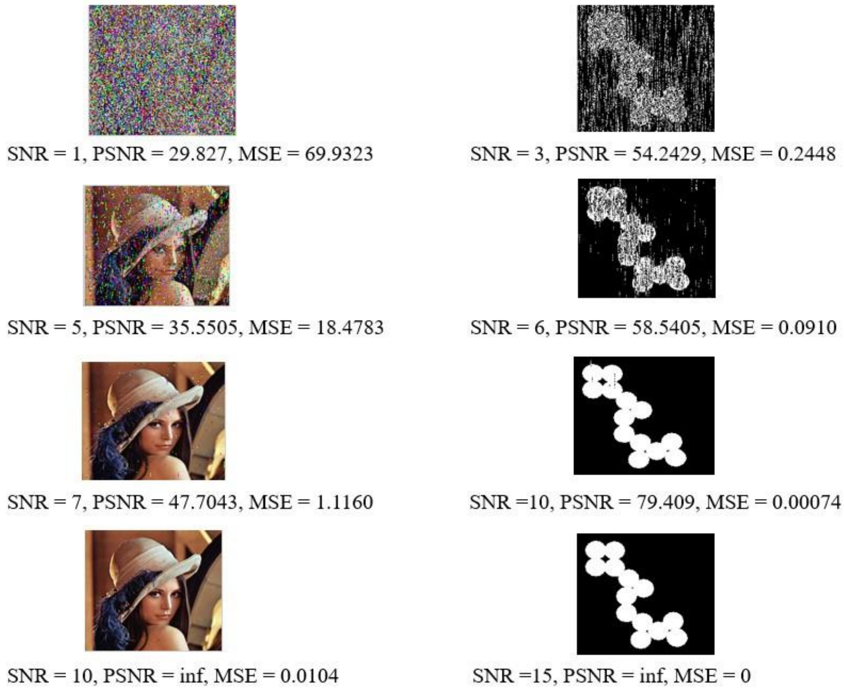

Figure 18. SNR, MSE and PSNR values for Colour and Binary Image using 16-QAM for MIMO-OFDM

4.2. OFDM Data Rates

The data rate calculation is as follows.

For OFDM data rates

$$\text{Data Rate} = (\text{Modulation coded bits per symbol} \times \text{Coded bits per OFDM frame} \times \text{Coding rate}) \div (\text{Overall spreading gain} \times \text{OFDM symbol total duration}) \quad (1)$$

Each 15MHz sub-channel has a data rate of 10.63 Mbps, and so there are 1024 sub-channels, resulting in a basic 10.63 Mbps x 1024 = 10,885.12 Mbps, or 10.886 Gbps. These data-rates are theoretical as per communication engineering as it is shown in Table 2, when these data rates are multiplied with clocks frequency of the processing system there is an increase in the data rate as per equation (1) to be multipled with operating frequency of the system. In case of DWT Cyclic Prefix must be zero to obtain to realise the FBMC.

Table 2. Data Rates for OFDM for 5G Applications

OFDM Coded Bits Modulation bit × FFT/DWT	FEC Code Rate	Frequency (MHz)	OFDM Symbol Duration	Cyclic Prefix	OFDM Data Rate (Mbps)
64-QAM (6 bits) ×256	1/2	20	124	4	120.00
64-QAM (6 bits) ×512	1/2	40	124	4	480.00
64-QAM (6 bits) ×512	1/3	40	124	4	316.80
16-QAM (4 bits) ×512	1/3	20	124	4	105.60
16-QAM (4 bits) ×512	1/2	20	124	4	160.00
64-QAM (6 bits) ×512	1/2	40	124	4	480.00
128-QAM (7 bits) ×512	1/2	40	124	4	560.00
128-QAM (7 bits) ×1024	1/2	40	124	4	1120.0

4.3. 4x4 MIMO-OFDM data rates

The data rate for the MIMO-OFDM system is given by equation (2):

$$\textit{MIMO-OFDM Data Rate} = (\textit{Number of MIMO Antennas} \times \textit{OFDM Data Rate}) \qquad (2)$$

Table 3. Data Rates for MIMO-OFDM for 5G Applications

OFDM Data Rates in Mbps	4x4 MIMO-OFDM Data Rate = (Number of Antennas × OFDM Data Rate) (Mbps)
120.00	480
480.00	1920
316.80	1267
105.60	422
160.00	640
480.00	1920
560.00	2240
1120.00	4000

Table 3 shows the data rates for the MIMO-OFDM system from the standpoint of communication engineering. MIMO-OFDM data rates are calculated by multiplying the number of antennas by the OFDM data rates. To achieve the actual data rate when the system is implemented with the embedded architecture one would have to multiply equation (2) with the clock frequency of the operating system and its implemented components.

4.4. 4x4 MIMO-OFDM Zynq UltraScale programmability and its data rates and timing

The implemented system was tested for frequencies of 100 MHz, 250 MHz, 500 MHz and 1000 MHz achieving a data rate in a range of 10 Gbps to 50 Gbps through software programming of the N-FFT and N-DWT over a Mali GPU procesor and programmable QAM implemented on the Programmable Logic (PL) and the parallel-to-serial (P/S) and serial-to-parallel (S/P) computations are implemented on PS along with other control software over the ARM-Cortex-A53 of the Zynq UltraScale device of the EG series. The device is interfaced with a 4x4 Dual AD9361 transreceiver (AD_FMCOMMS5-EBZ) as it is shown in Figure 6. The timing for different system implementation achieved from 150 to 300 msec for the above mentioned combinations. The computation complexity is higher for DWT in comparison with FFT-OFDM. The system is programmable and reconfigurable to achieve different functionalities as MIMO, OFDM, MIMO-OFDM, FBMC and MIMO-FBMC.

5. Comparative analysis of data rates and execution timing for the method proposed in this work and for other works in the existing literature

The comparative values obtained for the data rates are given in Table 4 and those obtained for the execution time are given in Table 5.

Table 4. Comparative overview of the data rates obtained in this work and in other works from the existing literature

Authors	MIMO-OFDM Data Rate Throughput
The Proposed Method	10.9 Gbps to 50 Gbps
Rani et.al. (2022)	10 Gbps
Agarwal et al. (2019)	1 Gbps
Suryawanshi et al. (2015)	1 Gbps
Venkataramanan & Lakshmi (2022)	100 Mbps
Kim et al. (2021)	18 Mbps

Table 5. Comparative overview of the values of execution time obtained in this work and in the existing literature

Authors	SoC Architecture Frameworks	MIMO-OFDM Execution Time (msec)	Comparison of implemented sub-components
The Proposed Method	Zynq UltraScale with ARM Cortex-A53 + Mali GPU + PL	300	Full MIMO-OFDM with programmability and reconfigurability
Singh et.al. (2021)	ARM Cortex A9	700	16-QAM, and 64-FFT
Dou & Zhang (2018)	STM32F407 Cortex-M4	2.88	64-FFT
Zitouni et al. (2017)	ARM Cortex-A9	--	--
Fadhil (2018)	FPGA	--	--

6. Conclusions and future work

The 5G technology provides high-speed low-latency connectivity, which is crucial for 5G applications. MIMO-OFDM technologies provide greater solution aid in increasing data rates. The impact of AWGN channels on the performance of combinations such as FFT-OFDM and DWT-OFDM has been analysed. The DWT-based OFDM system performed much better than the FFT-based OFDM system on AWGN channel in simulations but its embedded implementation is complex and computationally intensive. The BER performance of Haar and Daubechies wavelet transforms is almost identical as they are transmitted over AWGN channel. DWT can be adopted instead of FFT for frequency translation because DWT has a lower BER than FFT. The implementation of the MIMO-OFDM system provided a data rate throughput of 10 to 50 Gbps based on a frequency of operations of 100 MHz, 250 MHz, 500 MHz and 1000 MHz. The timing achieved for the system design execution ranged from 150 to 300 msec based on the different configurations of the FFT and DWT and N-order QAM. In the future the system shall be analysed in order to obtain the response time and data on communication availability and to implement user mobility support. Also, in the future a Multi-User MIMO could be implemented.

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