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Efficient Multi-Carrier Communication Systems: A Performance Evaluation of Parallel and Sequential Data Processing Models

Aseel Qasim[1*], Najlaa muhammed mohie[2], and Zainab Naser Azeez[3]

[1*]Department of Information Technology, College of Computer Science and Mathematics, University of Thi-Qar, Thi-Qar, Iraq. aseel.a.qasim@utq.edu.iq, https://orcid.org/0009-0001-9142-0152

[2]Department of Computer Science, College of Education for Pure Sciences, University of Thi-Qar, Thi-Qar, Iraq. najlaamuhammed.eps@utq.edu.iq, https://orcid.org/0009-0002-2231-9074

[3]Computer Techniques Engineering Department, Imam AlKadhum University College, Nasiriyah, Thi-Qar, Iraq. zainab.naser@iku.edu.iq, https://orcid.org/0009-0000-9949-7560

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Abstract

Orthogonal frequency division multiplexing (OFDM) is a popular method for multi-carrier transmission today. Nonetheless, one disadvantage of OFDM is its large peak-to-average power ratio (PAPR) which decreases the efficiency of power amplifiers. Orthogonal Wavelet Division Multiplexing (OWDM) offers an alternative to Orthogonal Frequency Division Multiplexing (OFDM). While OFDM utilizes the Inverse Fast Fourier Transform (IFFT), OWDM employs the Inverse Discrete Wavelet Transform (IDWT). Previous studies have shown that the Bit Error Rate (BER) for both OWDM and OFDM is nearly identical; however, OWDM features a lower Peak Average Power Ratio (PAPR) compared to OFDM. This research evaluates different wavelets' performance in implementing OWDM and designs two OWDM system models using hardware description language for FPGA implementation. The first design accomplishes data processing parallelly, while the second design processes data sequentially. The first design processes faster than the second one but takes up more resources. Specifically, the former algorithm uses 393 pins with 39% utilization of FPGA resources while the latter algorithm utilizes 73 pins with only 6% use of FPGA resources. Designers are allowed to opt between these proposed models depending on system requirements and available resources. FPGAs provide numerous advantages, including parallel processing power and substantial computational capabilities. The modelling and simulation were performed on the VCU118-XCVU9P-L2FLGA2104E FPGA board.

Keywords: Inverse Discrete Wavelet Transform (IDWT), Orthogonal Frequency-division Multiplexing (OFDM), Orthogonal Wavelet Division Multiplexing (OWDM).

1 Introduction

Previous mobile telecommunication technologies had a decrease in data bit rates with the limited spectrum resources caused by an increasing number of mobile phone users. To overcome this problem

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*Corresponding author: Department of Information Technology, College of Computer Science and Mathematics, University of Thi-Qar, Thi-Qar, Iraq.

and send huge amounts of data fast through narrow bandwidths, OFDM (Orthogonal Frequency-Division Multiplexing) which is a multi-carrier modulation has been extensively used (Jiménez-Carrión et al., 2023). Here, OFDM turns high-speed data streams into many low-speed streams. On the other hand, OFDM is not free from its limitations, especially the capacity constraints of the IFFT (Inverse Fast Fourier Transform) and FFT (Fast Fourier Transform) (Smith & Johnson, 2011). The performance of OFDM is degraded due to high PAPR (Peak-to-Average Power Ratio) resulting from numerous subcarriers (Brown & Wilson, 2013). Another candidate is called OWDM (orthogonal wavelet division multiplexing) (Patel & Gupta, 2015). In principle, OWDM resembles OFDM but employs wavelet transformations in place of FFT and IFFT (Kim & Park, 2021). To be more specific, OWDM uses IDWT (Inverse Discrete Wavelet Transform) and DWT (Discrete Wavelet Transform) (Wang & Zhang, 2023). OWDM achieves multichannel communication through filter bank implementation (Nguyen & Lee, 2017; Nguyen & Lee, 2017)

Validation of the theoretical benefits behind OWDM requires simulation as well as practical implementation. The purpose of this effort is to simulate OWDM and implement it using VHDL on Xilinx ISE software. The Virtex-7 Field Programmable Gate Array (FPGA) is employed for this implementation. By implementing OWDM on FPGA, we aim to achieve results that confirm the theoretical benefits of OWDM (Ariunaa et al., 2023).

Basic Theory

- **Orthogonal Wavelet Division Multiplexing**

OWDM is a multi-carrier transmission method as an alternative to OFDM, it uses Discrete Wavelet Transform (DWT) for modulation and de-modulation instead of the Fourier transform. Waste Orthonormal Discrete Multi-wavelet (OWDM) utilizes wavelet transform rather than Fourier transform. In OWDM, signal realization takes place in the telecommunication system using a filter bank- an N input and 1 output where at the transmitter incoming signals are generated (López et al., 2023). Every input is a sub-symbol of the main symbol, while output from the OWDM signal indicates the main symbol (Patel & Gupta, 2015; Jones & Garcia, 2021).

The bird's-eye view of the signal synthesis in OWDM is to combine different bright (luminous) and not illuminated pulses each carrying a weighted symbol. One input, multiple outputs filter bank is employed to analyze the signal at the receiver.

- **Wavelet Transforms**

The wavelet transform further reduces the complexity of both transmission side and receiving side systems as well as their subcarriers. Orthogonal subcarriers are generated using Discrete Wavelet Transform (DWT). The signal has to be passed through a high pass filter and a low pass filter for DWT. A high-pass filter (HPF) is used for the analysis of high frequencies and a Low-pass filter (LPF) This kind of filters are used to perform low-frequency analysis (Madhusudhana Rao et al., 2021; Pavithra et al., 2020). The mathematical relationships for DWT and its inverse (IDWT) are shown below (Smith & Johnson, 2022; Brown & Wilson, 2022).

$$C_{high}[\mathrm{k}] = \sum \mathrm{X}[\mathrm{k}].\,\mathrm{g}\ [2\mathrm{k}\ \mathrm{n}] \tag{1}$$

$$\mathrm{C}_{low}[\mathrm{k}] = \sum \mathrm{X}[\mathrm{k}].\,\mathrm{h}\ [2\mathrm{k}\ \mathrm{n}] \tag{2}$$

$$\mathrm{X}[\mathrm{k}] = \sum \left(C_{high}[\mathrm{k}].\,\mathrm{g}[2\mathrm{k}-\mathrm{n}]\right) + \sum \left(\mathrm{C}_{low}[\mathrm{k}].\,\mathrm{h}[2\mathrm{k}-\mathrm{n}]\right) \qquad (3)$$

In the given equations (1), (2) & (3), Chigh(k) represents the high-frequency signal, Clow(k) denotes the low-frequency signal, x(k) is the information signal, and g(k) and h(k) are the digital filter coefficients (Veerappan, 2023; Jamshidi, 2014). These equations describe the DWT algorithms, where Chigh(k) is obtained by convolving the signal with a high-pass filter (HPF), and Clow(k) results from convolving the signal with a low-pass filter (LPF).

The relationship X[k] pertains to the IDWT, where x[k] is the combination of the convolutions of Chigh(k) and Clow(k). These two sub-bands are called HPF and LPF, the output of which gets further divided as new signals at each stage along this division (sub-bands) for seamless tracing. For each input, a super-symbol-corresponding symbol associated with the super-symbol selected from a modulation scheme is generated. On the synthesis side, an OWDM signal is produced, which includes weighted OWDM pulses wherein each such pulse corresponds to one symbol in a super-symbol.

If we observe the DWT, it is found that there is little information in its lateral lobes and most data are concentrated in the main lobe so interferences have been minimized (Patel & Gupta, 2022). In this research, the Daubechies wavelet was used. The simple and effective Daubechies wavelet makes it a candidate for the study (Nguyen & Lee, 2022; Kim & Park, 2022). In particular, Figures 1 and 2 demonstrate how we process the discrete wavelet modulation data underpinning the generation of the OWDM signal production (top row) and OMDW signal reconstruction or recovery. This information is split into the high and low-frequency components according to the wavelet chosen. Then finally, a time series is the combination of all signaling in the block schema (Smith & Johnson, 2020).

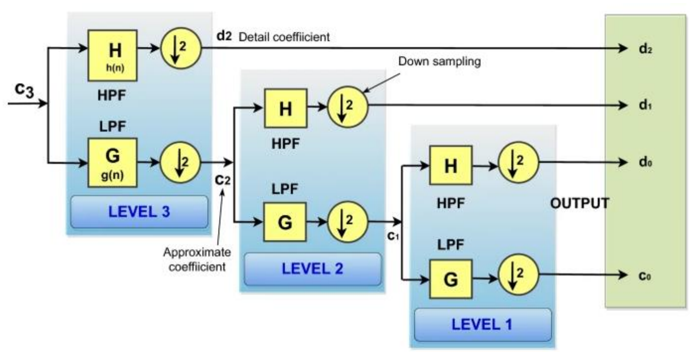

Figure 1: Filter Bank Structure for Signal Reconstruction in OWDM (Smith & Johnson, 2020)

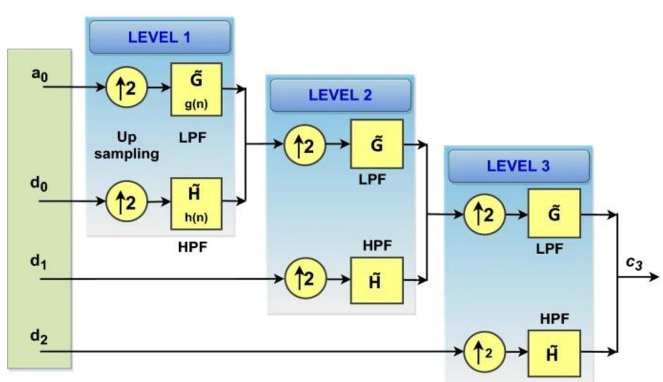

Figure 2: Filter Bank Structure for Signal Synthesis in OWDM (Smith & Johnson, 2020)

2 Literature Review

Several research papers have already suggested OWDM as a signaling technique for different applications over wide-ranging channel conditions. Most of those have claimed that it's a sufficient alternative to OFDM proving that it is less computationally complex and faster in processing time.

In general, the papers related to OWDM implementation can be divided into two parts. In the first section, some articles have designed and simulated the whole OWDM algorithm. In another state, the articles have optimized part of the OWDM implementation.

Introduction to OWDM and OFDM

Multi-carrier transmission is realized by employing Orthogonal Frequency Division Multiplexing (OFDM) which offers excessive spectral efficiency and is powerful towards multipath fading, making it an appealing candidate for a conversation machine. However, one of the most important risks of OFDM is its huge fee in Peak-to-Average Power Ratio (PAPR), which degrades energy amplifiers' performance (Kavitha, 2024; Brown & Wilson, 2020). Orthogonal Wavelet Division Multiplexing (OWDM) is proposed as an opportunity to improve this situation. OFDM is predicated on the Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) for modulation, but OWDM uses the IDWT and DWT. This distinction presents numerous advantages as nicely like decrease PAPR and viable improvement in Bit Error Rate (BER) performance (Mahapatra et al., 2016).

Simulation and Design Studies

A range of studies have been carried out to simulate OWDM structures and their layout. For example, within the research paintings of Lee, Kim and Choi (2000) a picture compression machine the usage of real-time FPGA-based DWT discrete wavelet rework changed into implemented nearly. This painting indicates the practical implementations of wavelet transforms which may be beneficial in designing numerous systems. Similarly, a green FPGA-based totally DWT system by Al-Falou and Ahmad (2006) in addition confirms the applicability of wavelet-based systems in real terms.

Implementation of FPGA

FPGA implementation of OWDM has been a main vicinity of studies because of its parallel processing nature and excessive computational efficiencies. Mahapatra et al. 2016, Graha et al. 2018 and Veena and Shanmukha 2019 applied parallel processing OWDM gadgets on FPGA and received upgrades in processing velocity and efficiency. This research emphasizes the parallel nature of the FPGA structure, which is properly suitable for the simultaneous processing required in OWDM systems.

Optimizations and Enhancements

Enhancing the overall performance of OWDM systems has been a subject of the latest studies, focusing on optimizing unique components. For instance, Garcia et al., (2017) explored the use of CORDIC to attain frequency synchronization in OWDM by improving its accuracy and decreasing computational load. These optimizations are full-size for successful deployments of OWDM into sensible communique structures.

FPGA-Based Hybrid Beamforming for 5G and Beyond

FPGA-based hybrid beamforming is essential for massive MIMO in 5G, balancing complexity and performance using combining analogue and digital strategies. FPGAs enable actual-time processing parallel computation, and assembly of the high demands of huge MIMO structures. Studies like (Jumaah et al., 2024) Spotlight stepped forward in pace and power efficiency in FPGA implementations. Integrating OWDM with hybrid beamforming should similarly beautify 5G performance, making FPGAs crucial for future wireless networks.

Applications and Future Directions

Various areas make use of OWDM including wireless communications, picture and video transmission, as well as record compression. Developments in FPGA technology especially concerning wavelet transforms make OWDM appear an attractive proposition in the direction of next-era communication systems. The destiny research guidelines are similar to the optimization of wavelet filters, adaptive wavelet transforms exploration and real-international deployment of diverse communique situations in the usage of OWDM systems (Nguyen & Lee, 2021).

To sum up, the literature on OWDM illustrates its potential as a cost-effective alternative for multi-carrier transmission other than the OFDM technique. The low PAPR together with almost identical BER performance coupled with parallel processing capabilities in FPGAs makes it promising for future communication systems. Continued research and development in this area will likely yield further enhancements and practical implementations of OWDM.

Implementation and System Analysis

- **System Diagram**

The OWDM system makes use of Discrete Wavelet Transform (DWT) for signal processing that reconstructs the transmitter process using Inverse Discrete Wavelet Transform (IDWT) and decomposes the receiver process using DWT. Serial-to-parallel conversion is necessary to change signals from the serial form into the parallel format and vice versa. Quadrature Amplitude Modulation (QAM) modulator/demodulator converts analog signals into digital, and vice versa. Convolutional encoding/decoding techniques are used to improve the quality of data transmission. Figure 3 gives a block diagram of the OWDM processing system. Two methods for implementing OWDM on FPGA are proposed in this study. In the first case, information is fed concurrently into an FPGA-based OWDM block leading to faster processing. The second one is the sequential application of data into FPGA which reduces the number of FPGA resources hence making it possible to use cheaper components. Figure 3 shows a block diagram of OWDM processing (Graha et al., 2017).

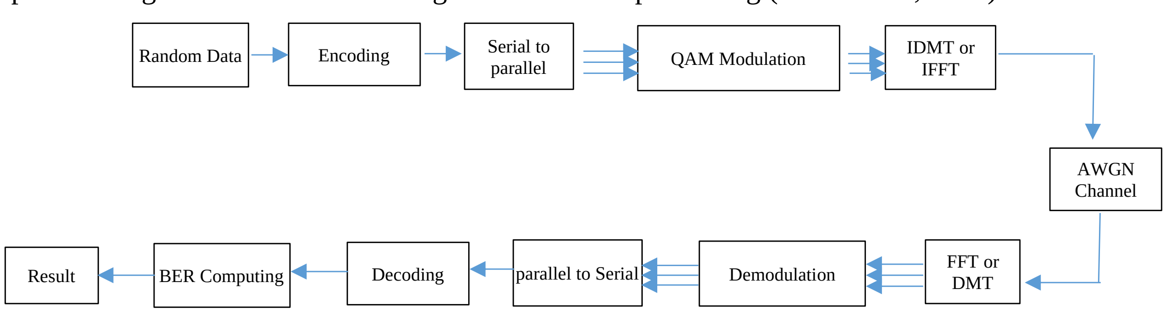

Figure 3: Block Diagram of the OWDM Transceiver System

Transmitter Side

- Serial-to-Parallel Conversion: Converts serial input data into parallel data streams.
- QAM Modulator: Modulates the parallel data streams into QAM signals.
- Convolutional Encoder: Encodes the QAM signals for error correction.
- IDWT: Reconstructs the signal using the inverse discrete wavelet transform.
- Parallel-to-Serial Conversion: Converts the parallel data streams back to serial form for transmission through the channel.

Channel

- The channel through which the signal is transmitted.

Receiver Side

- Serial-to-Parallel Conversion: Converts the received serial data back to parallel streams.
- DWT: Decomposes the received signal using the discrete wavelet transform.
- Parallel-to-Serial Conversion: Converts the parallel data streams back to serial form.
- Convolutional Decoder: Decodes the received signals to correct errors.
- QAM Demodulator: Demodulates the received signals back into digital data.
- Serial-to-Parallel Conversion: Converts the final parallel data streams back to serial form.

- **Implementation Methods**

Parallel Data Entry Method

- Data are entered into the OWDM block in parallel, allowing for faster processing.

Sequential Data Entry Method

- Data are applied sequentially to the FPGA, which reduces FPGA resource usage and allows for cost-effective component use.

- **Simulation Condition**

Table 1 shows the characteristics of the environment in which the simulation has been performed.

Table 1: The Environmental Conditions Used in the Simulation (Brown & Wilson, 2013)

Parameter	**Value**
SNR	0db - 40db
Modulation	16 QAM & 64 QAM
Wavelet	Daubechies
Channel	AWGN
Parameter	Value

- **Generating VHDL Code**

To implement VHDL code, we have used MATLAB software's latest feature for designing and testing HDL codes. However, this approach allows rapid HDL code testing and visualization of outputs with powerful MATLAB tools available in this framework as shown in Figure 4.

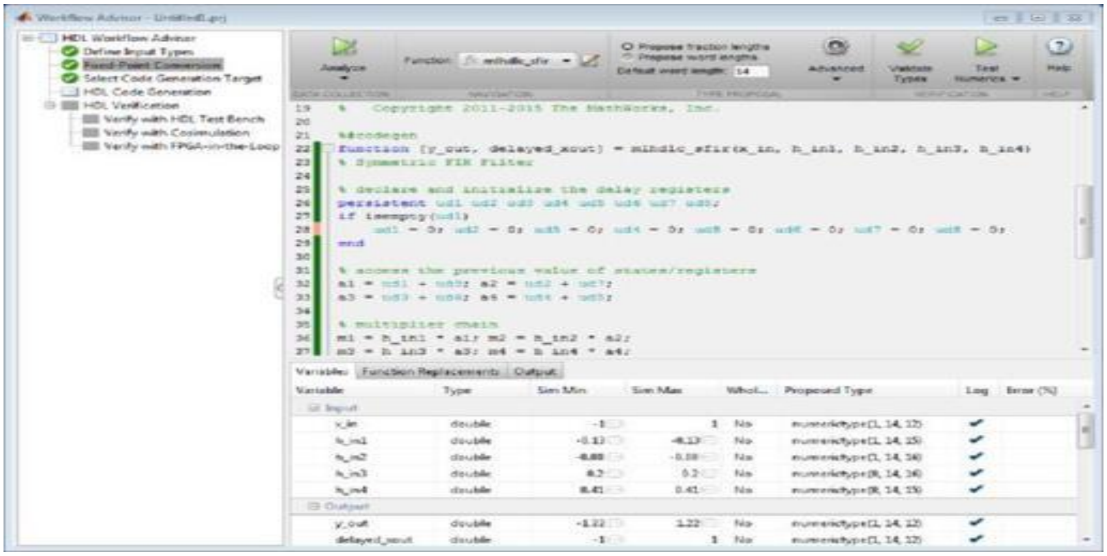

Figure 4: HDL Code Generation Process

- **Implementation of Proposed Methods**

An FPGA was used to implement the first method. It is this FPGA that we used in running OWDM. The specific model for OWDM is limited to eight sub-channels (Daubechies wavelet (db2)). In Figure 5, all data are simultaneously applied and confronted with the designed OWDM block. In the second implementation, data are entered sequentially into the OWDM system. Then two output data points are created for each entry time and consecutively sent to the transmitter, as shown in Figures 5 and 6.

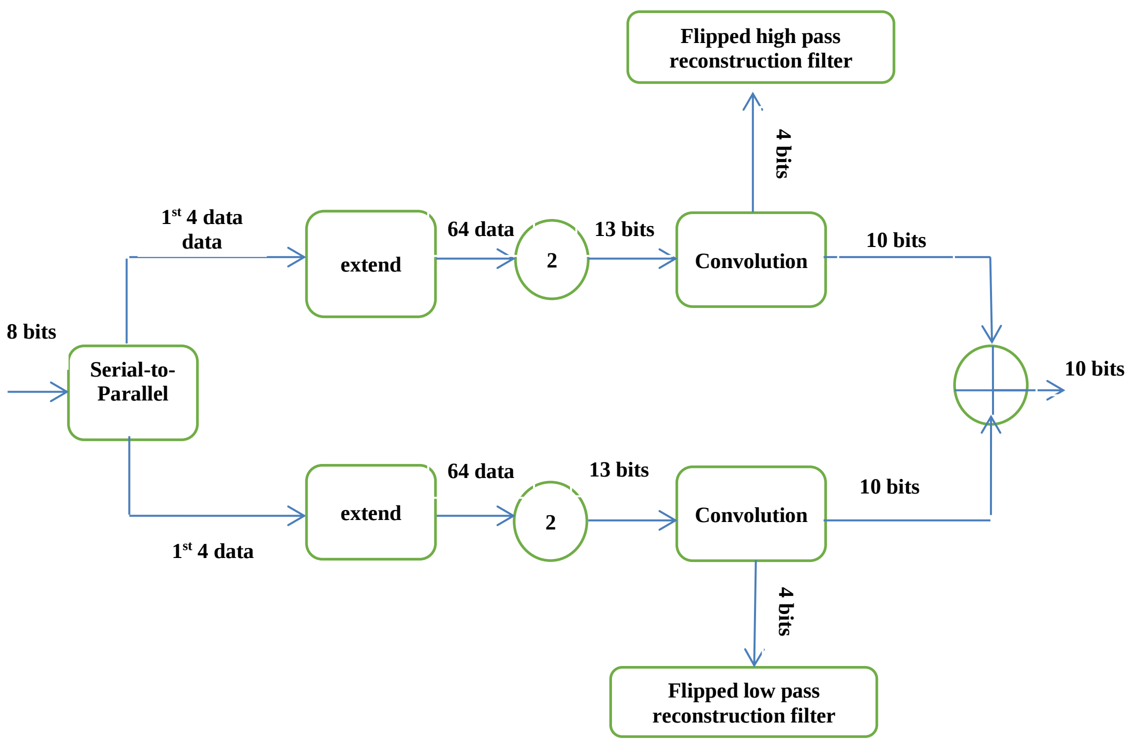

Figure 5: Block Diagram of Parallel IDWT Implementation (First Method) (Smith & Johnson, 2020)

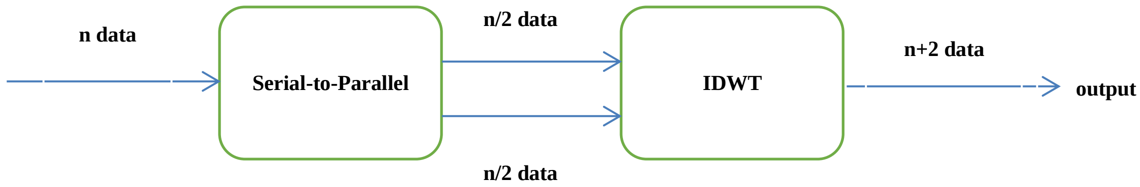

Figure 6: Block Diagram of Sequential IDWT Implementation (Second Method) (Smith & Johnson, 2020)

3 Simulation and Rustles

Performance Analysis of Beamforming Algorithms

Simulation and implementation of the two proposed methods on the FPGA board of the VCU118-XCVU9P-L2FLGA2104E FPGA are discussed.

- **Examination of Wavelet Families**

One of the research objectives of this thesis is to evaluate the performance of OWDM and OFDM systems. A comparison between these two modulations can be seen in Figure 7. From this graph (Brown & Wilson, 2020), it can be observed that the Haar family has quite similar performances across its members as a whole. As opposed to OFDM, it performs better than OFDM in terms of BER such as Haar and db32 among other things among other things. Well, generally speaking, significant similarity is clearly visible within both modulations in this context.

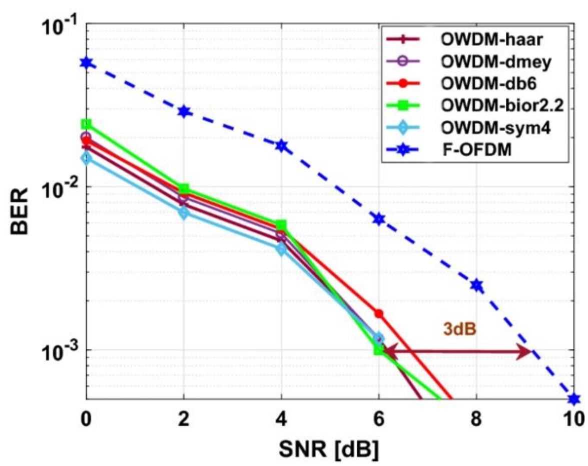

Figure 7: Performance Comparison of OFDM and OWDM for Different Wavelet Families

- **OWDM Implementation**

Just as earlier stated, there are two methods for implementing the OWDM. In the first method, since 8 data is entered into the system at the same time, a significant number of FPGA resources go into their implementation. These resources are in direct relationship with the number of inputs thus limiting the inputs that can be taken by the system based on its available resources. The new approach proposes to decouple the dependency of the system on numbers from those inputs as we enter data sequentially into it. Table 2 and Figure 8 present findings from method one.

Table 2: Resources Used in the First Proposed Method

Logic Utilization	Used	Available	Utilization
Number of SliceRegisters	30	866,400	1%
Number of SliceLUTs	117	433,200	1%
Number of fullyused LUT-FF pairs	28	119	23%
Number of bonded IOBs	7	1000	7%
Number of BUFG/BUFGM UXs	0	240	0%
Number ofDSP48A1s	24	3600	1%

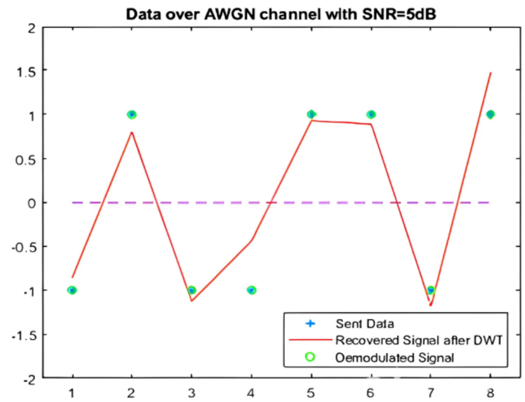

Figure 8: Input and Received Data in AWGN Channel with SNR = 5 dB (First Method)

The second method involves encoding a signal with 64 sub-channels by this system and reconstructing it at the reception point. Figure 9 shows examination results while resource requirements needed for achieving this design are also similar to what is found in Table 3.

Table 3: Resources Used in the Second Proposed Method

Logic Utilization	Used	Available	Utilization
Number of Slice Registers	0	866,400	0%
Number of Slice LUTs	129	433,200	1%
Number of fully used LUT-FFpairs	0	129	0%
Number of bonded IOBs	393	1000	39%
Number of BUFG/BUFGMU Xs	0	240	0%
Number ofDSP48A1s	68	3600	1%

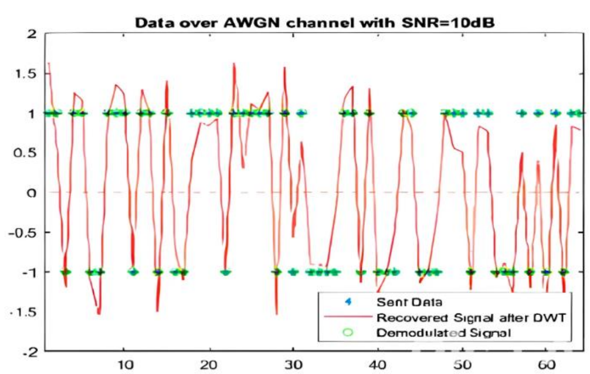

Figure 9: Input and Received Data in AWGN Channel with SNR = 10 dB (Second Method)

4 Conclusion

In this study, we compared the efficiency of different wavelets and found out that the type of wavelet used does not affect much the final quality of implementation. We decided to realize a sample OWDM system in hardware using a db2 wavelet for FPGA implementation. With that aim, two schemes were executed.

After evaluating the effectiveness of various OWDM wavelets, two VHDL instances were designed for implementing them on FPGA. In the first design, data enters into the processor at once while in the second design, data enter into the processor one after another. The first method is faster in processing and uses more resources than the second method. Specifically, 393 pins which represent 39% of all FPGA resources would be used for implementing logic using this approach; And 73 pins which represent 7% should be employed to realize logic by another one.

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Authors Biography

Aseel Ahed Qasim received a B.S.C Degree in Communication technical Engineering 2007 From Al-Furat Al-Awsat Technical University, Iraq, and an M.Sc. Electrical engineering communication system from Imam Raza International University 2020, Iran. She is now a lecturer in the Department of Information Technology, College of Computer Science and Mathematics, University of Thi-Qar, she has research interests in wireless communication, and antenna and includes applications.

Najlaa Muhammed Mohie received a B.S.C Degree in Computer science in 2013 From the College of Education for pure Science University of Thi-Qar, Iraq, and M.Sc. Computer Science 2019 From the College of Education for pure Science University of Thi-Qar, Iraq, she is now a lecture in Department of Computer science, College of education for pure science, University of Thi-Qar, she is research interests in image processor.

Zainab Naser Azeez received a B.S.C Degree in Computer science in 2013 From College of education for pure Science University of Thi-Qar, Iraq, and M.Sc. Computer science 2016 From College of education for pure Science University of Thi-Qar, Iraq, She is now a lecture in Computer Techniques Engineering department, Imam AlKadhum University College, she is research interests image processor, and big data.