Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.10 n.48, p. 155-161. July/August., 2024.

DOI: https://doi.org/10.5935/jetia.v10i48.988

RESEARCH ARTICLE OPEN ACCESS

A NOVEL DESIGN EMPLOYING ARBITRARY TREE STRUCTURE FOR ADAPTIVE THRSHOLDING DISCRETE WAVELET PACKET TRANSFORMATION

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ARTICLE INFO

Article History
Received: December 03th, 2023
Revised: July 31th, 2024
Accepted: August 16th, 2024
Published: August 30th, 2024

Keywords:
FIR Filter,
Wavelet packet transform,
Image processing,
Arbitrary tree structure,
Compression ratio.

ABSTRACT

Image compression is a very important technique in the realm of digital image processing. It acting as a key role in enabling effective storage area and data transmission rate of image data. Finite Impulse Response (FIR) filters have proven to be effective tools for image compression due to their linear phase response, which preserves image sharpness during the compression process. In this paper, we propose an innovative design of an FIR filter specifically tailored for effective image compression applications, leveraging the power of wavelet packet transform (WPT). Extensive simulations demonstrate that our proposed FIR filter outperforms conventional FIR filter designs and WPT-based compression methods in terms of both compression ratio and image quality. The filter effectively removes redundant information while preserving visual details, resulting in compressed images that are visually appealing and suitable for various applications. The filter coefficients are calculated serially, and the circuit complexity is decreased by rearranging the intermediate filter coefficients in addition to the memory elements. A 30% reduction in memory elements is required with the pipelined architecture that has been proposed. Additionally, the hardware implementation results demonstrate a 10% and 20% reduction in area and power requirements, respectively.

I. INTRODUCTION

Images are now commonplace in the digital age and are essential to education, entertainment, and communication. Uncompressed image files are large, though, and this presents storage and transmission issues. In order to facilitate effective storage and transmission, image compression techniques seek to reduce image file sizes without appreciably sacrificing visual quality. For many applications, such as digital storage, internet data transmission, and real-time image processing, image compression is essential. Compressed images in digital storage require less space to store, making device storage more effective and lowering storage expenses. Compressed images with less bandwidth are needed for Internet data transmission in order to speed up webpage loading and lower data transmission costs. Applications for real-time image processing, like video conferencing and medical imaging, are made possible by the compressed images' lower processing resource requirements. FIR filters' distinct qualities have made them effective tools for image compression. FIR filters prevent distortion or blurring of images during compression by maintaining a constant phase response across all frequencies. Different frequency responses can be used in the design of FIR filters to meet different compression needs.

Convolution operations can be effectively used to implement FIR filters, which makes them appropriate for real-time applications. For designing an efficient FIR filter for image compression, we need to consider certain features. The frequency response of the filter should efficiently eradicate high-frequency elements from the desired image. For that image contains the crucial details in the low-frequency elements. In order to attain the intended compression ratio and image quality, the filter coefficients are carefully selected. Both mathematical methods and empirical analyses are frequently used in this optimization. In order to guarantee effective implementation and appropriateness for real-time applications, the filter design should minimize computational complexity. Wavelet packet transform (WPT) is an effective method for breaking down and analyzing images. It breaks down an image into a collection of wavelet subbands, each of which stands for a distinct frequency range. Selective filtering according to the frequency content of each subband can be accomplished by applying FIR filters to it. The method known as "adaptive FIR filtering" modifies the filter's properties to fit the unique frequency content of each wavelet subband. This method applies suitable filtering to various subbands to balance compression efficiency and image quality. FIR filters have a number of benefits when it comes to image compression. FIR filters' linear phase response makes sure that during compression, image sharpness is preserved. FIR filters are flexible tools for an extensive assortment of applications because they can be adjusted to different image types and compression requirements.

When compared to conventional FIR filtering techniques, wavelet packet decomposition and adaptive filtering techniques can drastically reduce computational complexity. FIR filters are appropriate for a variety of image compression applications because of their credentials. The FIR filter can accomplish maximum compression ratios while conserving tolerable image quality. FIR filters have shown to be useful instruments for image compression, making it possible to store and transfer image data in an efficient manner. They are excellent choices for a variety of image compression applications due to their linear phase response, adaptability in design, and computational efficiency. FIR filters are useful tools for digital image processing because they can achieve high compression ratios without sacrificing image quality by combining wavelet packet transform and adaptive filtering techniques.

Our proposed FIR filter design integrates two key aspects:
Wavelet Packet Decomposition: The image is decomposed into a set of wavelet subbands using WPT, allowing for selective filtering based on the frequency content of each subband.
Adaptive FIR Filtering: FIR filters with varying characteristics are applied to each wavelet subband based on its frequency content and compression requirements. This adaptive approach balances compression efficiency and image quality.

The following is how the work is structured. The fundamentals of Image compression techniques and the relation of wavelet filter are covered in Section II. The theoretical underpinnings of WPT and the implementation of WPT in filter are described in Section III. Section IV presents a comprehensive summary of the existing methods and current research work. Future research directions are provided in Section V, which wraps up the essay.

II. EXISTING WORK

Discrete wavelet transforms (DWTs) are capable of performing multi-resolution signal analysis with both space (time) and frequency domain locality adjustments. DWT may be used to break down signals into different subbands with frequency and time information. The performance improvement in terms of image restoring capacity and clarity is better for Discrete Wavelet Transform than DCT. Furthermore, the compression ratio of DWT is high. As a result, DWT can be employed widely in signal and image processing applications such as JPEG2000, MPEG-4, and others. Subsampling followed by the use of FIR filters is the typical way that DWT is implemented. Due to its enormous computational load, numerous research projects aim to develop novel algorithms. Because a lifting scheme for DWT requires substantially fewer computations, it can be implemented easily. The wavelet transform's spatial justification serves as the foundation for this entire procedure. It also possesses the capacity to generate new mother wavelets. Extensive advancement has been carried out in the context of DWT in the domain of VLSI in the form of DSP and FPGA implementation. Adaptive thresholding can remove more noise than traditional methods without sacrificing important signal features. The processing of such components can be realized with Multipliers. The processing speed is depending on clock rate of the proposed architecture. The number of multipliers required for a pipeline stage in the architecture related to clock rate of the system. As per [1], the dispensation rate and number of multipliers present in the biggest obstacles of the hardware implementation of I-D DWT. However, the primary problem with 2-D DWT is memory, which also accounts for the majority of hardware complexity and cost. The cause is the power consumption and on-chip memory limitations. Nonetheless, the critical path has a Tm + Ta. In this case, the adder and multiplier delays are Ta and Tm, and the Effective folded architecture (EFA) computation takes a considerable amount of time.

Lin and Wu designed an DWT architecture using pipeline structure with a smaller number of delays reduces to Tm critical path. The designed pipeline structure has a temporal memory size has a limit of 4N number of operations [2]. However, because scanning is done using a single input, single output method, processing speed cannot be increased. Lai et al. [3] implement parallel 2-D DWT. The stated architecture follows pipeline method with 2 inputs and 1 output. Though this structure follows pipeline style, it requires 8 more pipeline stages to implement 1D-DWT. A flipping DWT architecture was proposed by Huang et al. [4]. Five pipeline stages with a single multiplier delay are used in this instance. However, a few pipelining stages can cause a considerable delay in the critical path and have a large temporal buffer. By recombining the intermediate values of the result, the number of pipeline stages and registers can be reduced. The shortcomings of earlier work can be addressed by the suggested lifting scheme, which also minimizes memory and logic sizes without sacrificing throughput. The critical path delay is Tm at this point, but it can be reduced to Ta by utilizing the shift add technique. Furthermore, the parallel scanning method is used to reduce the buffer size. As a result, our design can yield higher effectiveness.

The implementation of 2D-DWT concentrates on realizing small memory size with high-speed architectures. The separable approach is a technique that breaks down a group of wavelets into 1-D wavelets. This procedure will provide a simple way to implement the 2-D DWT. Even though this transform is simple to implement with a 1-D architecture, but it requires a large amount of memory space to be implemented [5]. Furthermore, processing an image with such an architecture would cause significant predicted misrepresentations. Filter architecture based on non-separable approach have been presented in [6] for overcome the aforementioned issues. Efficient architectures that optimize both area and time have been proposed in [7], utilizing a SIMD array or a parallel filter. Another architecture has been proposed in [8], which uses pipelines to provide high-speed, low-power performance based on a modified recursive pyramid algorithm. In addition to that, filter architecture designed using pipeline structure that will be performed parallelly for reducing the processing time [9]. A systolic array-based architecture for the multidimensional DWT that requires little hardware complexity has been proposed in [10]. Most non-separable 2-D architectures have been projected to deliver low hardware complexity. The low hardware complexity will be associated with little regard for computing time or throughput. These two parameters are two critical factors in an architecture designed for DWT real-time applications. The Fourier basis, or complex exponentials, works well for smooth signals in most cases, but not so well for discontinuous signals or signals with both high- and low-frequency components. This is primarily due to the Fourier basis's subpar time resolution characteristics. Although the Short Time Fourier Transform (STFT) can help with this situation, it has a significant drawback. As the width of the window is constant, the high and low frequency portions are need to be captured. These activity causes issues with resolution. Wavelets were developed to address these constraints.

Wavelet basis is ideal for a variety of applications due to its flexibility in adapting to limited fluctuations in the signal. This is because broader windows can be used in the low frequency provinces of the signal and thinner windows for high frequency regions. Both types of windows have been used for allowing better resolution of the signal. Applications for wavelets include seismology, signal analysis, and image processing. Wavelet transform is widely used for image compression, offering notable enhancements in image quality at higher compression ratios compared to traditional methods. The Discrete Wavelet Transform is the transformation applied in JPEG 2000. The dual-tree complex wavelet transforms, which results in the Hilbert transform pair of wavelet bases. The wavelet bases can be used to get around some of the disadvantages of the discrete wavelet transform (DWT). The performance degradation is mainly due to lack of shift invariance and poor directional selectivity. A linear phase's condition is crucial for many filter bank applications. We require filters with symmetrical coefficients in order to achieve linear phase, and this cannot be done with compactly supported orthogonal wavelets. Several authors [11] and [12] have described designing bi-orthogonal wavelets that can form Hilbert transform pairs and yield symmetric filter coefficients. However, the author of [11] suggested using multipliers to implement a single level 1-D biorthogonal Hilbert transform pair on an FPGA. That implementation raises the cost and complexity of the hardware. This paper proposes an improved design that addresses this drawback.

III. PROPOSED WORK

The Wavelet Algorithm Transform and the Discrete Cosine Transform (DCT) are two methods that can be used to compress images. DCT divides images into sections with different frequencies. The term "lossy" refers to the discarding of less significant frequencies during the step quantization, which is typically where part of the compression happens. The image compression process is then retrieved using only the most crucial frequencies. Because of this, there is some distortion in the reconstructed image; however, this distortion can be altered in the compression phase. The reconstructed image below shows some loss of quality, but it is still easily identifiable despite the removal of nearly 85% of the DCT coefficients. Images require a lot of storage space, high transmission bandwidths, and extended transmission times due to the amount of information they contain. As a result, it is critical to compress the image by saving only the data that is absolutely necessary for reconstructing it. An image is a matrix of pixels which contains the specific intensity level. In order to compress an image, it is important to take advantage of redundancies in the image, such as areas with little to no change in pixel values. The maximum area covered by the same colour represents large redundancies in images. While images with frequent and large colour changes produce less redundancy and are more difficult to compress.

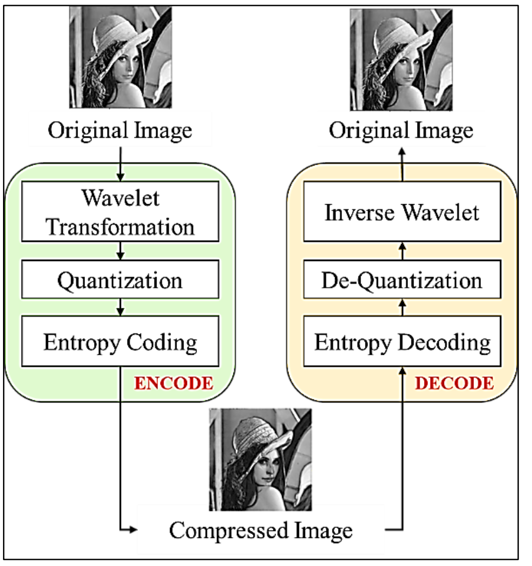

Figure 1: Block Diagram of Image compression and decompression using DWT.
Source: Authors, (2024).

The DWT is generally consisting of three key stages: entropy coding, quantization, and transformation. The encoding and decoding procedures, which involve performing the stages in reverse to create a decoder, are shown in Figure 1. The decoding process involves only one distinct step, which is de-quantization, followed by an inverse transform to roughly recreate the original image. Wavelet analysis is a technique that can be used to separate an image's information into approximate and detailed sub-signals. These sub-signals can then be used to compress the image. The three important factors in the sub-signals represent the parallel, perpendicular, and oblique information or deviations in the image. However, the approximation sub-signal displays the overall trend of pixel values. If the factors are extremely small, the above-said factors can be set as zero without modify the given image. The threshold is the value below which information is deemed to be sufficiently small to be set to zero. The amount of condensation that can be accomplished upsurges with the number of zeros. The energy retained by an image is proportional to the sum of the squares of the pixel values. The energy represents the amount of information reserved by the image after condensation and decondensation.

A compression is referred to as lossless if all of the original energy is preserved, allowing for an exact reconstruction of the image. The information in the image has not changed means, the setting threshold value is zero. Lossy compression is the process of losing energy when any values are altered. While it is desirable to have the maximum number of zeros and energy retention during compression, it is essential to strike a balance between the two because the more zeros obtained, the more energy is lost.

III.1 WAVELET PACKET TRANSFORM (WPT)

Tree-structured filter banks are used to implement DWPT and DWT. The output of the low pass filter (LPF) is further administered to compute the subsequent stage coefficients. The output of the high pass filter (HPF) is taken into consideration as the outcome of the DWT computation. The outputs of the High pass and low pass filter play a vital role in computation of DWPT coefficients. The signal is broken down and down sampled using DWPT for multi-resolution analysis in order to produce approximated. Also, the process includes detailed coefficients at each resolution level. The computation of the DWPT involves a three-level tree, as illustrates in Fig. 2. The figure demonstrates that the frequency band obtained from the previous one is used for the decomposition at a level. The output of the low pass filter (LPF) yields the approximated coefficients at each level, while the output of the high pass filter (HPF) yields the detailed coefficients at each level 123. The signal flow graph (SFG) has used for matching the discrete wavelet packet transforms (DWPT) to a pipeline architecture. The SFG for mapping DWPT is similar to the SFG of the fast Fourier transform (FFT). The SFG's butterfly computes the level-specific high pass and low pass coefficients. Conversely, the tree-structured filter bank is directly mapped to a direct-mapped (DM) architecture.

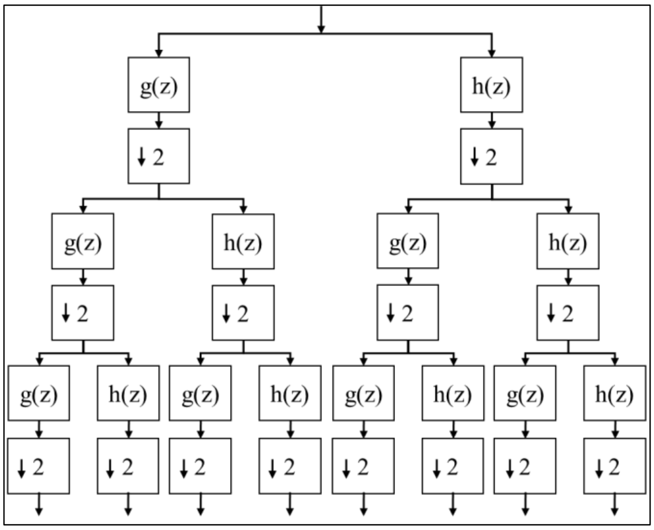

Figure 2: 3 Level Wallace Tree Structure.
Source: Authors, (2024).

III.2 ADAPTIVE THRESHOLD BASED WAVELET PACKET FILTERING

Swelden [13] introduced the lifting scheme. It is a productive way to calculate DWT/DWPT. As per [14], all category of filter coefficients can be factorized obsessed by a series of adaptive thresholding values. The polyphase matrix is factorized using the Euclidian algorithm. A diagonal normalization matrix consists a number of superior and inferior triangular matrices. They are the products of factorization. In this case, K is a constant and *si* (z) and $ti\ (z)$ are Laurent polynomials.

$$P(Z) = \begin{bmatrix} h_e(z) & g_e(z) \\ h_o(z) & g_o(z) \end{bmatrix}$$

$$\prod_{i=1}^{m} \begin{bmatrix} 1 & S_i(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ t_i(z) & 1 \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & 1/K \end{bmatrix} \quad (1)$$

A highpass subband is produced by computing the superior triangular matrix. Similarly, a low pass subband is generated by processing the inferior triangular matrix. At last, the outputs are scaled by K and $1/K$ in turn. The computational complexity of the DWPT/DWT is reduced by almost 50% with the polyphase factorization method compared to the convolution method [10].

Time and frequency analysis on the filter coefficients is very important for signal and image processing. The time and frequency analysis on filter coefficients can be computing by using the discrete wavelet transform (DWT). A popular numerous-resolution method for characteristics abstraction, image condensation, and image de-noising is discrete wavelet decomposition. The input image is divided into four substitute bands by the standard discrete wavelet, which are LL, LH, HL, and HH. The LH, HL, and HH substitute bands provide the horizontal, vertical, and diagonal information of an image, respectively, while the LL substitute bands provides approximate coefficients, or the average image. Figure 3 displays the DWT decomposition. The low-pass substitute bands in WPT following the initial level of decomposition is called the LL substitute bands. Stated differently, this substitute bands comprises the lowest frequencies present in the original signal. Since the LL substitute bands has the most significant information, it is frequently used as an approximation of the original signal. Since the LL subband is crucial for maintaining the image's visual quality, it is frequently used in image compression. The image can be compressed significantly with minimal loss of quality by removing the other substitute bands, which primarily contain noise and high-frequency information. The horizontal details of the original signal are contained in the LH sub-band, which is the horizontal detail sub-band. This indicates that it has data regarding the edges of the objects in the picture.

The vertical details of the original signal are contained in the HL sub-band, which is the vertical detail sub-band. This indicates that it has details regarding the textures of the image's objects. The diagonal details of the original signal are contained in the HH sub-band, which is the diagonal detail sub-band. This indicates that it has details about the edges and corners of the objects in the picture. Applications for the LL, LH, HL, and HH sub-bands are diverse. The most crucial sub-band for maintaining the image's visual quality is the LL sub-band. The picture can be greatly compressed with minimal quality loss by removing the other sub-bands, which are primarily composed of noise and high-frequency information. LL, LH, HL, and HH sub-bands can be applied to images to reduce noise. Since the noise in the image is usually concentrated in the higher-frequency sub-bands, the noise can be eliminated from the image by removing these sub-bands.You can use the LH, HL, and HH sub-bands to extract features from your photos. Subsequently, these characteristics can be applied to tasks related to image processing, such as object identification and classification.

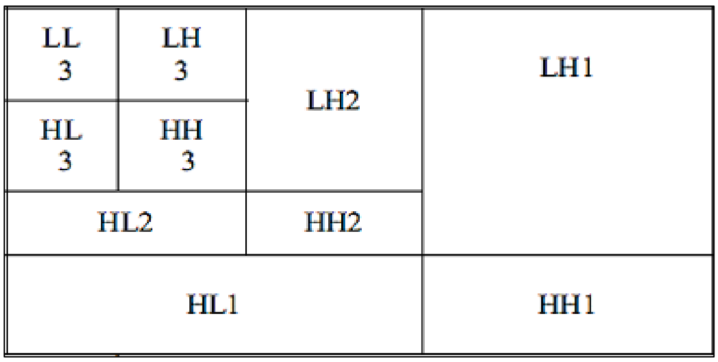

Figure 3: Discrete Wavelet Transform Decomposition at the Third Level.
Source: Authors, (2024).

Since the LL subband contains the majority of the important information, only the average coefficient, or DWT, is further broken down in pyramidal DWT. However, some of the dominant data might still be present in the HH, HL, and LH subbands. Due to the fact that the LH, HL, and HH subbands in an image contain an object's contours in the horizontal, vertical, and diagonal directions [15]. Therefore, each subband is further broken down using a DWPT-based method. A generalization of discrete wavelet analysis, discrete wavelet packet transform (DWPT) analysis further breaks down the detail (LH, HL, and HH) and approximate (LL) coefficients at each level. As a result, the DWPT offers the most comprehensive signal analysis and is better suited for feature extraction in multiple directions [13, 14]. A full tree produced by the DWPT is displayed in Figure 4.

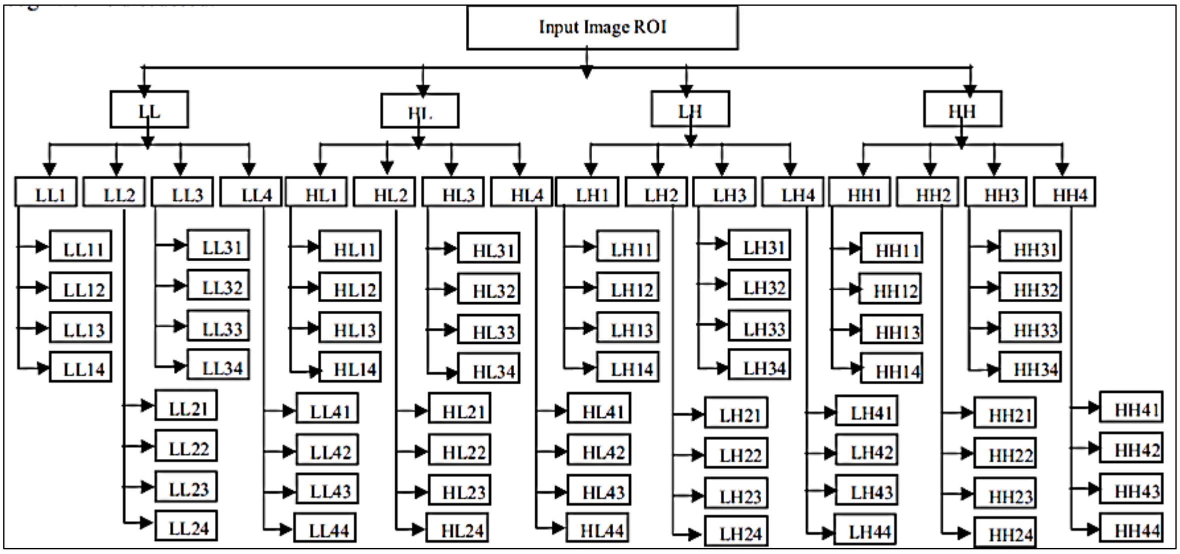

Figure 4: Complete Tree for Discrete Wavelet Packet Transform Decomposition.
Source: Authors, (2024).

III.3 FIR FILTER DESIGN

The signal and image processing applications relies on filter design for its operation. Generally, filter is frequently utilizing determinate impulse response (FIR) and detached wavelet transform (DWT). The N-tap FIR filter's associated equation is provided by equation (2).

$$Y(n) = \sum_{i=0}^{N-1} x(n-1)h(i) \quad (2)$$

The filter (h) consists of discrete filter coefficients X, and it includes the range {h(i): i=0,1,..., N-1}. Figure 1 depicts the traditional, straight-forward, and inverse FIR filter designs. In case the multiplier, adder tree delays and adder are Tm, Tat, and Ta, respectively. The parameter called critical path of the straight form filter is (Tm + Tad). Whereas the opposite form's critical path is (Tm + Ta). The basic DWT transform can be realized by employing convolution-based enactment with FIR-filters. At each transform level, the input discrete signal X(n) is filtered by a low-pass filter (h) and a high-pass filter (g). The low-pass subband YL and high-pass subband YH are then created by simply dropping the alternate output samples in each of the two output streams. The related equations (3) can be written [16].

$$y_L(n) = \sum_{i=0}^{\frac{N}{2}-1} h(2n-i)x(i), \quad y_H(n) = \sum_{i=0}^{\frac{N}{2}-1} g(2n-i)x(i) \quad (3)$$

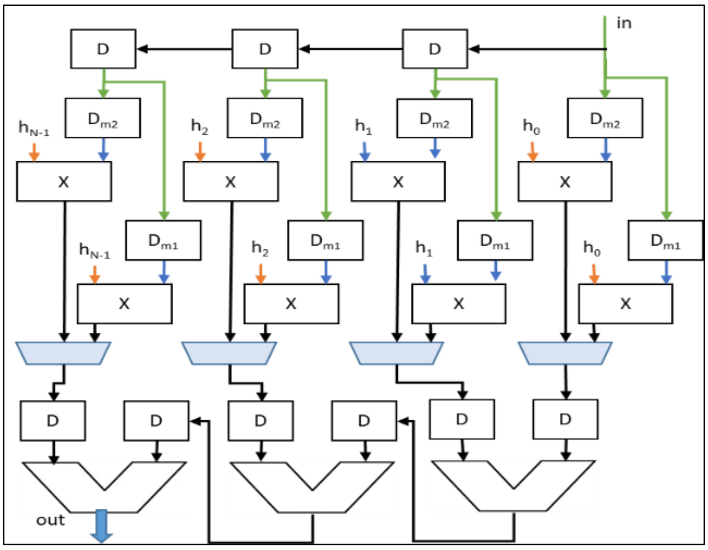

Figure 5: The proposed FIR Filter Architecture based on WPT.
Source: Authors, (2024).

Our fundamentally new non-symmetric N-tap FIR filter architecture, which makes use of the alternate multiplication and D-latches distribution, is depicted in Figure 5. The suggested architecture's critical path is Tm/2 (assuming Ta < Tm/2) where Tm is the multiplier delay. By using symmetric FIR filters, an area-efficient architecture can be achieved, resulting in an extremely high processing rate. In this architecture, filter coefficients are multiplied in parallel with the input data samples. The multiplication results are then stored by the D-latches for a single clock cycle. The filter outputs are then produced by the new adder tree adding up all of the stored products [17].

IV. RESULTS AND DISCUSSION

This section covers the design of the FIR filter using wavelets and the rectangular window method. For varying values of filter order, N, we compare the frequency response of the intended response with that of the designed filter. The two parameters taken into consideration for our study are the mean square error and the percentage overshoot. The proposed design has been simulated in Xilinx Vivado suit and Modelsim. Figure 6 and 7 illustrates the simulation result of proposed WPT based FIR filter and its area utilization report.

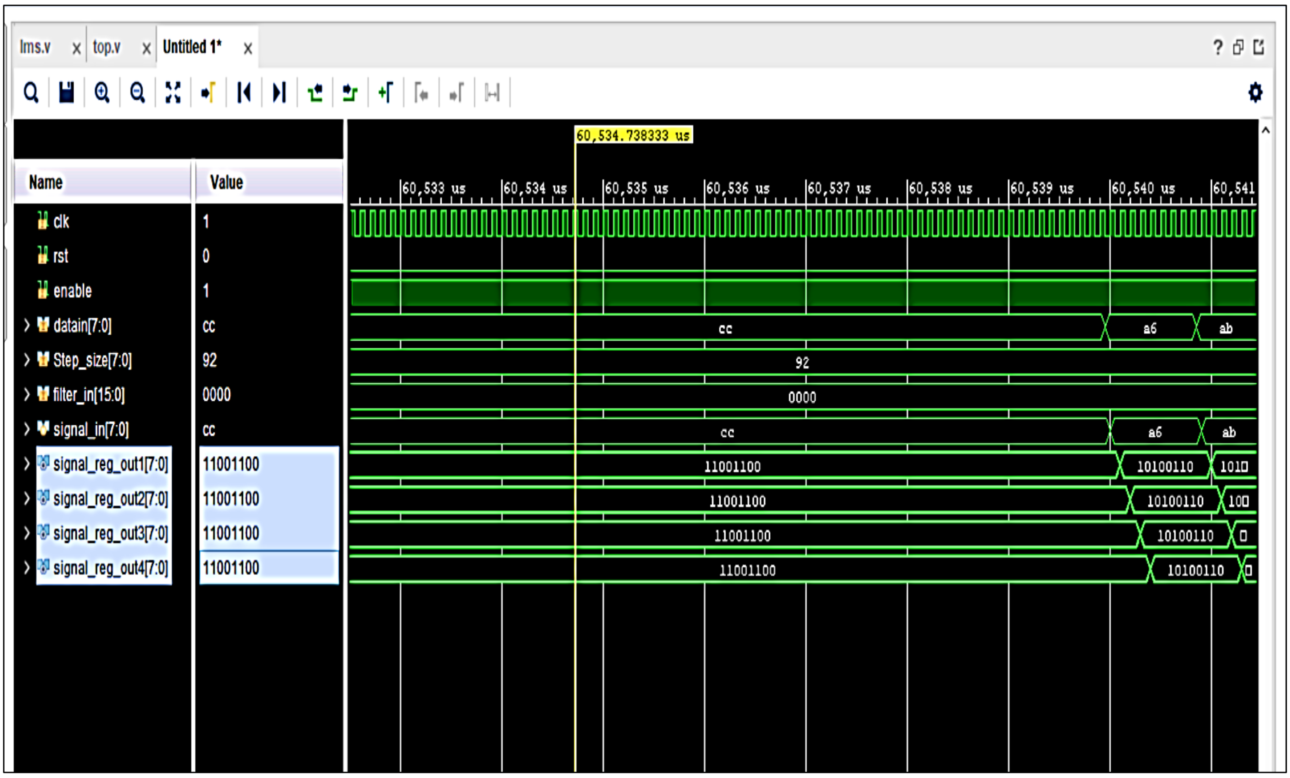

Figure 6: Simulation results for the proposed FIR filter using WPT
Source: Authors, (2024).

Resource	Estimation	Available	Utilization %
LUT	308	303600	0.10
FF	96	607200	0.02
DSP	4	2800	0.14
IO	51	600	8.50
BUFG	1	32	3.13

Figure 7: Area Utilization Report.
Source: Authors, (2024).

Table 1: Comparative Analysis of the proposed work.

Parameters	[18]	[19]	This work
Area in μm^2	17654	18964	16763
Power in Watt	0.0237	0.0376	0.0187
Gate count	3167	3782	2478

Source: Authors, (2024).

Table I displays a comparison between the proposed circuit and a previously published circuit. Garcia et al [19] proposed an architecture which explains the initial computation regarding generalized wavelet packet tree. This type of architecture exhibits very flexible design for the generalized amendment on wavelet packet tree. From this observation, the output wavelet filer coefficients require double the amount of sample size of the memory. Since the proposed wavelet level module is utilized periodically in computation, it cannot be applied to an incessant data flow. To the best of our knowledge, the architecture presented is the first register-based design that uses registers smaller than the sample size. This feasibility is very complicated to compute the comprehensive wavelet packet tree for continuous data flow. This one is very adaptable because it uses registers and multiplexers to support a generalized wavelet packet tree. The Virtex-7 FPGA (field-programmable gate array) was used to implement these circuits, and 250 MHz was used to calculate power. The Synopsys DC compiler with the 90-nm library is used to calculate area. As mentioned, when compared to the outcomes of the current methods, the area and power requirements of the proposed circuit are lowered to 10% and 20%, respectively.

V. CONCLUSION

This brief designates a proposed architecture that uses bit exchange circuit and adaptive thresholding based bypassed wavelet filter to compute a generalized wavelet packet tree. The data flow that the filter processes is constant. This brief introduces the reordering mechanism and filter, which save a large number of memory elements and hardware, contributing to the architecture's high area- and power-efficiency. It is preferred over the previous architecture when calculating an arbitrary tree DWPT, as can be seen from a comparison. The DWPT coefficients for the continuous data flow are computed simultaneously by the suggested architecture.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Author One, Author Two and Author Three.
Methodology: Author Two and Author Three.
Investigation: Author One and Author Two.
Discussion of results: Author One, Author Two and Author Three.
Writing – Original Draft: Author Two.
Writing – Review and Editing: Author One and Author Two.
Resources: Author Two.
Supervision: Author One.
Approval of the final text: Author One, Author Two and Author Three.

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