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VLSI Implementation of 3-Parallel FIR Filters through Coefficient Symmetry Property and Fast FIR Algorithm

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Abstract:-In multirate digital signal processing systems, polyphase filters are frequently used. The challenges in multirate digital signal processing systems primarily relate to efficiently processing signals at different rates while maintaining high-quality output. These challenges include computational complexity, power consumption, and signal delay. The coefficient symmetry property plays a key role in systematically arranging of filter taps in symmetric manner to improve operating efficiency. With a major focus on using the coefficient symmetry characteristic, this paper addresses the VLSI implementation of traditional Type-1 polyphase FIR filters. Furthermore, this paper incorporated 3-parallel FIR filters especially for sequences with odd lengths in order to take full advantage of the coefficient symmetry characteristic. The Fast FIR Algorithm (FFA) method is used to increase overall efficiency. Furthermore, in order to achieve better performance, a modified FFA technique is introduced to enhance overall performance. The paper thoroughly investigates important VLSI factors, such as power consumption, utilization, and delay, and shows how, by utilizing coefficient symmetry and applying this modified FFA technique, filters that are optimized for both power consumption and area utilization are able to be implemented. The results illustrate a significant reduction in both area and power consumption, particularly for longer filters, attributed to the reduced number of multiplication operations inherent in the fast FIR algorithm approach. Additionally, image processing application using 3x3 FIR filter is executed.

Keywords*: multirate systems, polyphase finite impulse response filters, coefficient symmetry, fast finite impulse response algorithm, image processing.*

1. Introduction

Digital Signal Processing (DSP) systems are the foundation in modern technology, operating exclusively in the digital domain for precise control and real-time processing. They offer adaptability through easily modifiable algorithms, ensuring accuracy in mathematical operations. This adaptability is crucial for various tasks, including audio and video streaming. Moreover, digital signals inherently resist noise and interference.

VLSI-based DSP systems merge dedicated hardware like custom-designed VLSI chips with software on general-purpose CPUs or GPUs, emphasizing compact and efficient processing within integrated circuits. They are vital in diverse VLSI applications, from telecommunications to image and audio processing. Proficiency in VLSI-based DSP principles empowers engineers and researchers in VLSI design to create customized chips for emerging technology needs, promoting technological advancement and enhancing signal processing within VLSI systems.

FIRfilters are widely used in a variety of industries, including audio processing, image enhancement, communications, Internet of things (IoT), and biomedical signal analysis due to its ability to give linear phase characteristics and guarantee stability.Filtering is the foundation of Digital Signal Processing (DSP) systems, playing a pivotal role in noise reduction and signal enhancement in applications like audio and image processing and biomedical signal processing. Polyphase Finite Impulse Response (FIR) filters are favored over direct form FIR filters due to their efficient utilization of coefficient symmetry, which accelerates computational processes. The filter taps are divided into several phases or subfilters. The input signal is divided into corresponding subfilters, each of which is separately filtered using the associated subfilters. The final output is obtained by combining the filtered subfilters. The Type-1 polyphase FIR filter's transfer function may be expressed as [1]-[3].

$$H(z) = \sum_{k=0}^{J-1} z^{-k} E_k z^J \qquad (1)$$

where,

$$E_k(z) = \sum_{l=0}^{\left\lceil \frac{N}{J} \right\rceil - 1} h_{Jl+k} z^{-l} \qquad (2)$$

Here, N denotes the order of the filter, J for the number of parallel subfilters connected to it, and $\left\lceil \frac{N}{J} \right\rceil$for the subfilter order of the polyphase structure.

The quality of having a symmetrical arrangement of filter coefficients is known as coefficient symmetry. One side of the center tap's coefficients mirrors or is symmetrically related to its opposite side. For N^{th}order FIR filter,n^{th}coefficient equals $(N-1-n)^{th}$ coefficient.This may be used to design the filter using [N/2] multiplier units rather than N multiplier units, while keeping the same number of delay and adder units.

The digital signal processing technique of convolution is made more effective by the Fast FIR Algorithm. The overall idea of FFA is to reduce the number of multiplication operations as the multiplication is the strongest operation and it is complex to design whereas addition operation is considered as weak.

Minimizing power consumption is vital in VLSI design for enhanced energy efficiency and battery life, while optimizing chip area utilization is crucial for reducing manufacturing costs and improving the performance of integrated circuits, particularly in real-time applications like multimedia, communication systems, and digital signal processing.

A highly effective method for constructing linear phase FIR filters within the RSRC while utilizing the coefficient symmetry characteristic was provided in references [4] and [5]. As the filter length increases, the complexity of multiplication reduces by around half. In [6], effective mathematical equations are derived for polyphase FIR filters that take use of coefficient symmetry without the need for further processing. Furthermore, it is possible to build M-parallel FIR filters using polyphase decomposition. In typical M-parallel FIR filters, M order polyphase substructures are aligned in M parallel units and the subfilters are then arranged in the required output order. As the parallelism increases, complexity increases as well. As a result, a novel strategy utilizing the fast FIR algorithm is used to minimize the number of multiplication operations.

As a result, the majority of the effort is on leveraging FFA [7]–[12] to reduce the number of multipliers. The typical technique to FFA was applied in [7] and resulted in a reduction in the number of processing units. In order to make parallel systems less difficult, a variety of FFA algorithms have been developed [8]–[9]. Additionally, modified FFA have been presented by [10]–[12] for the use of linear phase FIR filters. After that, the work was expanded as in [13]–[14], which presented a more effective parallel FIR filter based on the Cook-Toom algorithm, although it only included FIR filters of even length that are multiples of 2 and 3.

The following are the sections of the paper: The fundamental concept of polyphase FIR filters with coefficient symmetry is presented in the first part. In the following, VLSI implementation of polyphase FIR filters that exhibit the desirable coefficient symmetry quality is mentioned. Then, M-parallel FIR filters based on polyphase coefficient symmetry with the application of FFA and various cases in FFA are covered in the next section and one image processing application. Next follows the results, and finally the conclusion.

2. Objectives

Leveraging Coefficient Symmetry: To investigate and utilize the coefficient symmetry property of polyphase FIR filters for the purpose of arranging filter taps symmetrically, with the goal of enhancing operational efficiency.

VLSI Implementation: To develop a practical and efficient VLSI implementation for traditional Type-1 polyphase FIR filters, considering factors such as area utilization, power consumption, and signal delay.

3-Parallel FIR Filters: To incorporate 3-parallel FIR filters specifically designed for sequences with odd lengths, aiming to maximize the benefits of the coefficient symmetry characteristic.

Fast FIR Algorithm (FFA): To utilize the Fast FIR Algorithm (FFA) method as a means to increase the overall efficiency of the implemented filters by reducing the stronger operation i.e., multiplication operation.

Modified FFA Technique: To introduce and evaluate a modified FFA technique, designed to enhance the overall performance of the implemented filters.

VLSI Factors Investigation: To thoroughly investigate VLSI factors including power consumption, utilization, and demonstrate how the use of coefficient symmetry and the modified FFA technique can optimize filters for both power efficiency and area utilization.

Reduction in Area and Power Consumption: To present results illustrating a significant reduction in both area and power consumption, particularly for longer filters, attributed to the reduced number of multiplication operations inherent in the fast FIR algorithm approach.

Image Processing Application: To perform image smoothening and image enhancement application using 2x2 and 3x3 FIR filter.

3. Methods

1) Polyphase FIR Filters

Polyphase FIR filters represent a specialized and efficient approach within the realm of Finite Impulse Response (FIR) filters. These filters are designed to streamline the processing of multi-rate digital signals, making them particularly valuable in various applications. The key principle behind polyphase FIR filters is the decomposition of a traditional FIR filter into multiple polyphase components, each handling a subset of the filter's coefficients. This decomposition allows for parallel processing of different branches, significantly reducing computational complexity and making polyphase FIR filters an excellent choice for real-time and resource-constrained scenarios. Coefficient symmetry is crucial in the design of filters and in signal processing because it can simplify these processes. When coefficients exhibit symmetry, they demonstrate a mirrored pattern, which effectively reduces the number of unique values. This reduction in uniqueness brings about several benefits including improved computing effectiveness, simplicity of processes like convolutions and memory resource conservation. Additionally, symmetric coefficients usually result in more stable filter responses, which adds to the general reliability and robustness of the systems in which they are used. Coefficient symmetry is a key tool in the arsenal of signal processing and filter design Engineers because of this feature. The Type-1 polyphase FIR filters overall transfer function employing coefficient symmetry [6].

where, p=N-J ⌈N/J⌉+J, 0≤k≤J-1 and 0≤l≤⌈N/J⌉-1

Since, $h_n = h_{N-1-n}$ (3)

$h_{Jl+k} = h_{N-(Jl+k)-1}$ (4)

where, k is the subfilter and l is the nth coefficient of h_n within it, k' or k'' is the subfilter that complements k. In this instance, u is the index of corresponding symmetric coefficients of k' or k'' subfilter, so that N-(Jl+k)-1=Ju+k'(or Ju+k''). For N=16 and J=4, the Type-1 polyphase FIR filter's transfer function utilizing coefficient symmetry is [6].

$$H(z) = \sum_{k=0}^{3} z^{-k} \left(\sum_{l=0}^{1} h_{4l+k} z^{-4l} + z^{-8} \sum_{u=0}^{1} h_{4u+k} z^{-4(1-u)}\right) \quad (5)$$

The polyphase FIR filter leveraging coefficient symmetry is implemented using (5) is shown in Figure 1.

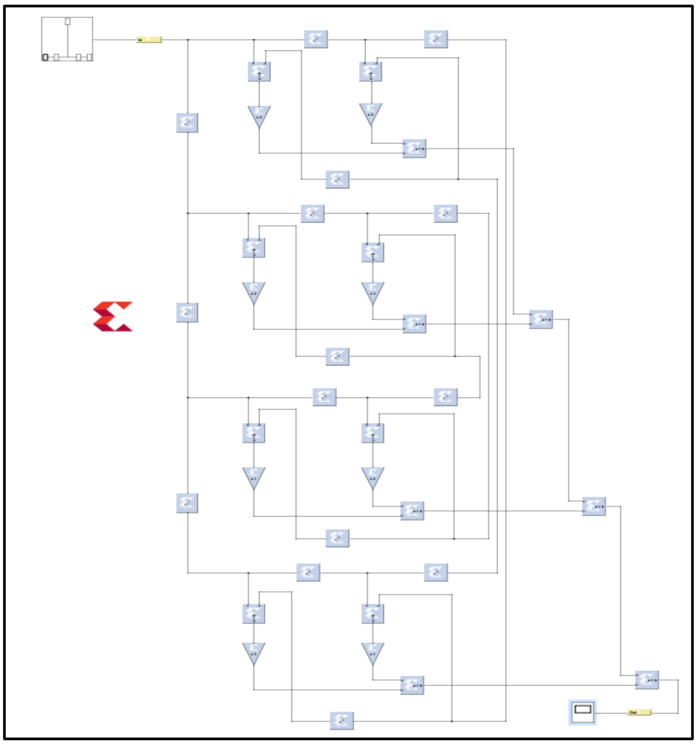

Figure 1: Type-1 polyphase FIR filter using coefficient symmetry property for N=16, J=4

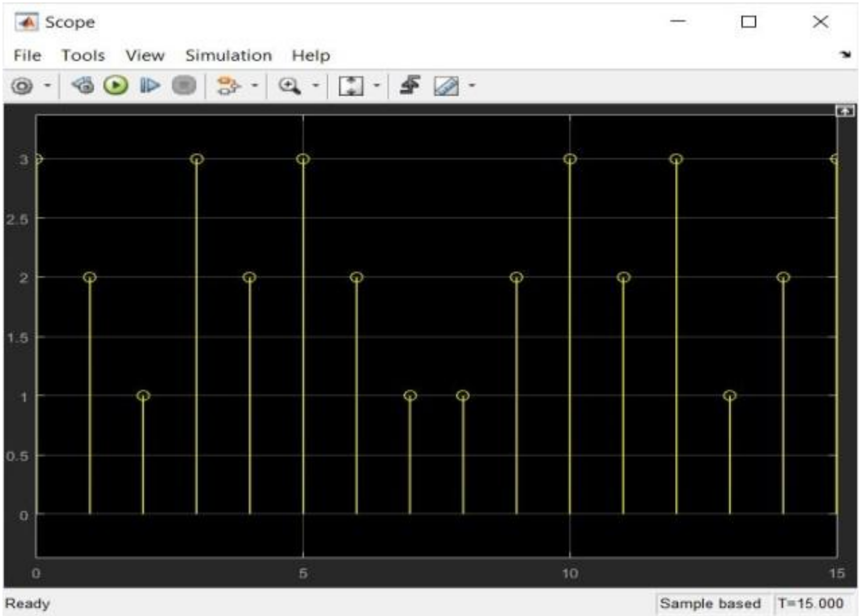

Figure 2: Output of a Type-1 polyphase FIR filter with coefficient symmetry is shown for the values N=16 and J=4.

By using this property, the higher index coefficients got eliminated i.e. from h_8 to $h_{15}$and lower index coefficients from h_0 to $h_7$replaced them as shown in Figure 2. The computing effectiveness is enhanced through the strategic use of coefficient symmetry. Coefficient symmetry simplifies computations by reducing the number of unique values in filter coefficients. By utilizing this property, there is reduction in number of coefficients by half. Furthermore, this property is leveraged in 3-parallel FIR filters and also took the advantage of modified fast FIR algorithm for better performance.

2) 3-Parallel FIR Filters

M-parallel FIR filters are a specialized configuration within the realm of digital signal processing, particularly focusing on finite impulse response (FIR) filtering. In this setup, multiple FIR filters, often sharing a common design, operate concurrently to process an input signal simultaneously. The primary objective behind employing M-parallel FIR filters is to significantly enhance processing speed and overall computational efficiency, a feature particularly valuable in real-time signal processing applications. In this arrangement, the input signal is systematically distributed among the M parallel filters, with each filter assigned the task of processing a designated portion of the signal. This parallelized approach results in a noteworthy reduction in processing time when contrasted with the sequential operation of a single filter. M-parallel FIR filters find their practical utility in applications characterized by high data rates or where computational efficiency plays a pivotal role. Such scenarios include communication systems, image processing tasks, and multimedia applications, especially when dealing with large datasets.

A digital signal processing setup called a 3-parallel FIR filter is made to simultaneously process three input phases and generate three output phases. This parallel processing architecture is very helpful in cases where simultaneous filtering or processing of many input signals is required. Three input streams are processed concurrently using a shared set of FIR filter coefficients in a 3-parallel FIR filter. The identical filtering process is individually applied to each input stream using the same coefficients for each of them.

The Fast Finite Impulse Response Algorithm (FFA) technique is based on the fundamental idea of lessening the computing load of multiplication operations. Instead, the FFA algorithm prioritizes addition operations heavily since they are computationally more effective and relatively easier. The computing performance of Fast FIR algorithms is greatly increased by reducing multiplication operations.In the time domain, an N tap FIR filter may be represented as [16].

$$y(n) = h(n) * x(n) \qquad (6)$$

$$y(n) = \sum_{i=0}^{N-1} h(i)x(n-i) \qquad (7)$$

where n may be any positive integer from 0 to infinity, x(n) is an input sequence of length n, and h(n) is the coefficients of a FIR filter of order N. The output y(n) is the convolution of input sequence and impulse response. Then, the standard M-parallel FIR filter may be derived through polyphase decomposition [16].

$$\sum_{p=0}^{M-1} y_p Z^M Z^{-p} = \sum_{q=0}^{M-1} X_q Z^M Z^{-q} \sum_{r=0}^{M-1} H_r Z^M Z^{-r} \qquad (8)$$

$$X_q(z) = \sum_{k=0}^{\infty} Z^{-k} x(Mk+q) \qquad (9)$$

$$H_r(z) = \sum_{k=0}^{\frac{N}{M}-1} Z^{-k} h(Mk+r) \qquad (10)$$

$$Y_p(z) = \sum_{k=0}^{\infty} Z^{-k} y(Mk+p) \qquad (11)$$

for p, q and r=0,1,2,3,…M-1. The 3-parallelel FIR filter (M=3) have the following equations:

$$Y_0 = H_0X_0 + Z^{-3}(H_2X_1 + H_1X_2) \qquad (12)$$

$$Y_1 = H_1X_0 + Z^{-3}H_2X_1 + H_0X_1 \qquad (13)$$

$$Y_2 = H_2X_0 + H_1X_1 + H_0X_2 \qquad (14)$$

The traditional 3-parallel FIR filter is implemented that uses (12), (13) and (14) as shown in the Figure 3. The choice of (N mod 3) determines one of three possible configurations for the 3-parallel FIR structure depicted by [13]. In this paper, the two scenarios of N mod 3=0 and N mod 3=1 taken into account.

A) 3-parallel FIR filter (N mod 3=0)

The subfilterH_1 is self-symmetric demonstrating that it possesses symmetry within itself whereas H_0 and H_2 are symmetric to each other implying that they share symmetrical characteristics, according to theorem 1 of [6].

Here, the 0th and 1stpolyphasesubfilter multipliers may be decreased by half by using the coefficient symmetry condition. To increase efficiency, the 2ndpolyphase filter might be changed into FFA. Therefore, (14) has to be changed. It is possible to rewrite the transfer function with output Y_2 as

$$Y_2 = H_2X_0 + (X_1 + X_2)(H_0 + H_1) - H_0X_1 - H_1X_2 \qquad (15)$$

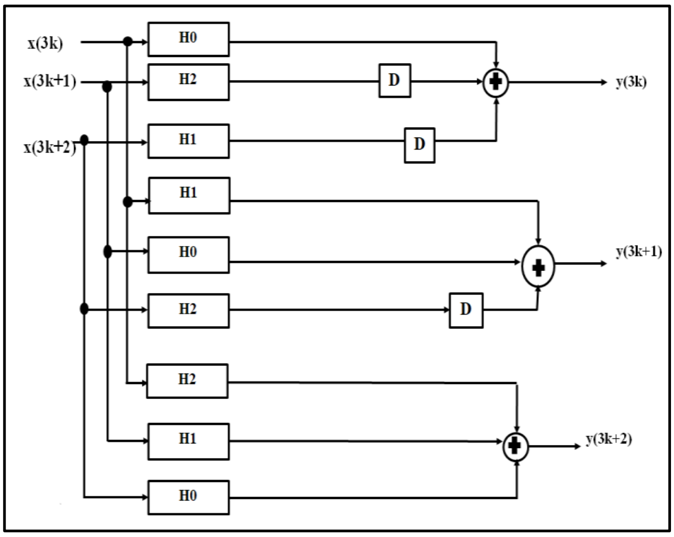

Figure 3 Traditional 3-parallel FIR filter

There is no need to multiply again since the additional terms in this case will be processed because the other two equations have already dealt with them. Now, utilizing (12), (13), and (15), the 3-parallel FIR filter has been developed for odd length filter for the case (N mod 3=0), as illustrated in Figure 4.

The significance of this strategic approach lies in its ability to optimize the computational efficiency of the filter while upholding its fundamental functionality. By leveraging the coefficient symmetry within the subfilters and adopting the Fast FIR Algorithm (FFA) technique, the filter effectively reduces the overall number of multiplications required, thereby enhancing its processing speed and minimizing computational complexity. This approach guarantees that the 3-parallel FIR filter can effectively manage odd-length filters, aligning with the precise demands of the signal processing task in progress, all the while upholding its fundamental functionality and effectiveness.

B) 3-parallel FIR filter (Nmod3=1)

The subfilterH_0 is self-symmetric demonstrating that it possesses symmetry within itself whereas H_1 and H_2 are symmetric to each other implying that they share symmetrical characteristics, according to [6]. Here, the 0thand 1stpolyphase filter multipliers may be reduced by half by using the coefficient symmetry condition. To increase efficiency, the 2ndpolyphase filter might be changed into FFA. Therefore, (14) has to be changed. It is possible to rewrite the transfer function with output Y_2 as

$$Y_2 = H_0X_2 + (X_0 + X_1)(H_1 + H_2) - H_2X_1 - H_1X_0 \qquad (16)$$

There is no need to multiply again since the additional terms in this case will be processed because the other two equations have already dealt with them. The resultant subfilter becomes self-symmetric when FFA is applied in a way that results in the addition of two subfilters which are symmetric to each other in this case.Now the 3-parallel FIR filter for odd length sequence of N for the case (Nmod3=1) is implemented using (12), (13), (16) as illustrated in Figure 5.

This strategic approach streamlines the computational process by eliminating redundant multiplications while taking full advantage of coefficient symmetry within the subfilters. It leads to the creation of a 3-parallel FIR filter optimized for odd-length sequences (when N mod 3=1), aligning the filter's design precisely with the unique characteristics of the given signal processing task. This optimized design preserves the filter's core functionality and ensures efficient processing.

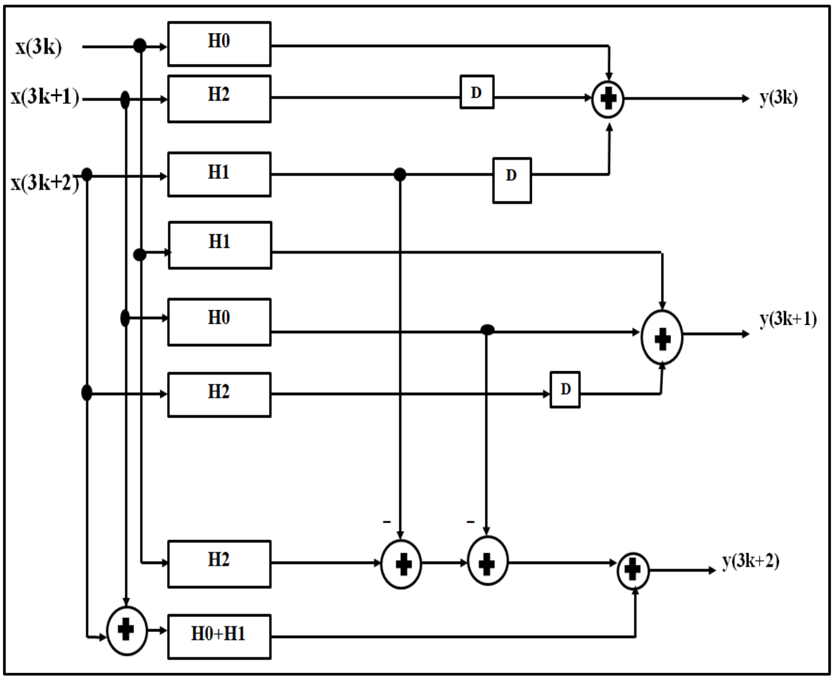

Figure 4 M-Parallel (M=3) FIR Filter after the application of modified FFA for odd sequence of N (Nmod3=0).

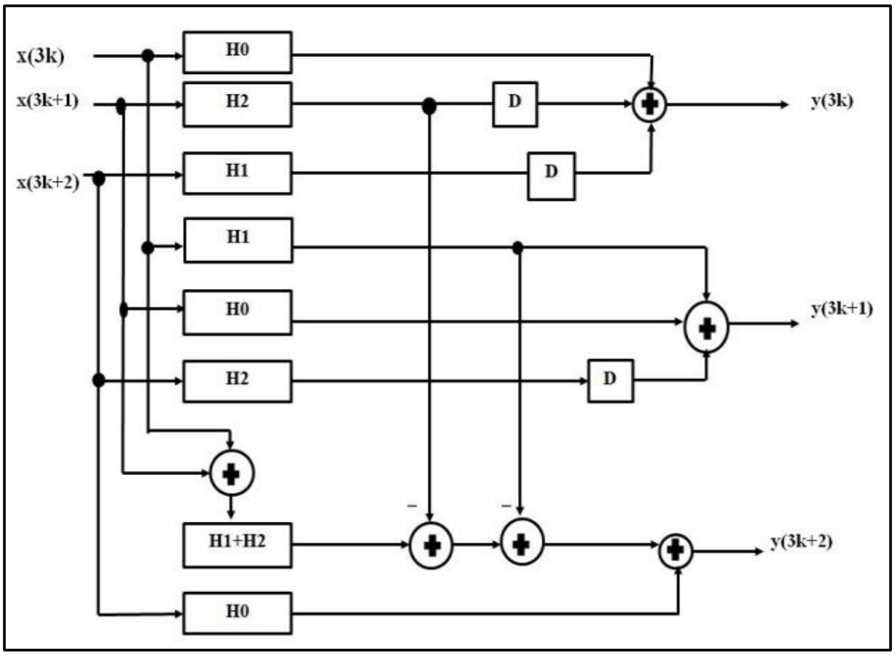

Figure 5 M-Parallel (M=3) FIR Filter after the application of modified FFA for odd sequence of N (Nmod3=1).

Computing effectiveness is improved by strategically leveraging coefficient symmetry and employing the Fast FIR Algorithm (FFA). Coefficient symmetry reduces the computational complexity by minimizing the number of unique filter coefficients, simplifying calculations. FFA prioritizes addition operations over multiplication operations, which are computationally more efficient. By reducing the reliance on multiplication operations, computing effectiveness is enhanced. Reduction in multiplication operations is achieved through the modified

FFA technique. FFA, as an algorithmic approach, is designed to minimize multiplication operations, which are typically more computationally intensive than addition operations. The modified FFA optimizes the filter design, further reducing the number of necessary multiplication operations while maintaining the desired filtering results.

3) Image Processing

In the field of image processing, both two-dimensional (2D) and three-dimensional (3D) Finite Impulse Response (FIR) filters play pivotal roles in enhancing and smoothening visual content. The utilization of a 2D FIR filter for image smoothening is examined where a 3x3 filter kernel is convolved with the image to reduce noise and produce a smoother rendition of the original. This operation showcases a common application of FIR filters in image processing, involving the convolution of image data with filter coefficients in two dimensions.

In parallel, 3D FIR filters extend this concept to three-dimensional data, often employed in video processing or the temporal processing of image sequences. While 2D and 3D FIR filters represent conventional FIR filter applications, type-1 polyphase FIR filters and 3-parallel FIR filters can be related in the sense that these are specialized FIR filter implementations configured for certain signal processing needs.

Polyphase filters, for example, optimize FIR filter processing by reducing computational complexity, making them particularly useful in applications like multirate signal processing. Similarly, 3-parallel FIR filters operate in parallel, enhancing efficiency in certain signal processing tasks. Here, image smoothening using a simple 2x2 FIR filter is performed and then enhances the image by convolving it with a defined 3x3 FIR filter. The resulting enhanced image is displayed alongside the original and smoothened images as shown in Fig. 6.

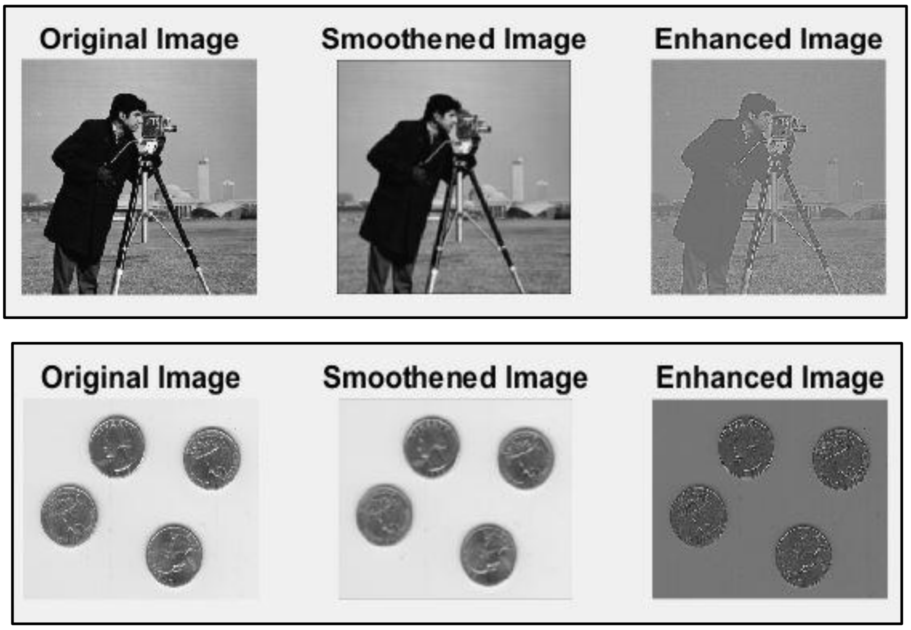

Figure 6 Image smoothening and image enhancement using 2D and 3D FIR filter (a) (b)

In image processing, smoothing and enhancing visual content involve applying Finite Impulse Response (FIR) filters. These filters work by convolving the input image with a predefined filter kernel. Smoothing is achieved by reducing noise in the image, while enhancement involves improving overall image quality. This process effectively modifies pixel values based on the convolution operation, resulting in a visually improved image. FIR filters are widely used in many applications as it has linear phase characteristics and stability.

4. Results

Low power consumption is a key objective in VLSI design for improved energy efficiency and extended battery life in electronic devices. In this research, power consumption reduction is achieved through the optimized design of FIR filters. Leveraging coefficient symmetry ensures that computations are more efficient, reducing the overall energy required for signal processing. Additionally, the modified FFA technique reduces the number of multiplication operations, which are typically power-intensive, further contributing to reduced power consumption. To reduce signal processing delay, the research focuses on optimizing FIR filters. The delay is minimized by simplifying the filter design and minimizing computational complexity. This ensures that signals are processed more efficiently, resulting in reduced delay.

With the use of coefficient symmetry and FFA, consider a 3-parallel FIR filter for odd length sequence e.g. N=25 (Nmod3=1) as illustrated in Figure 6. The coefficient symmetry requirement allows for the substitution of the coefficients h(24), h(23),...h(13) with h(0), h(1), h(2),..., h(12). In order to replace H_2 and H_1 with a new subfilter, FFA is used, and the assistance of (16) results in the creation of new subfilter $(H_2 + H_1)$.Notably, there is a reduction in power consumption and area while applying modified FFA for different odd values of N values as the number of multiplication operations decreases. Similarly, for the case N mod 3=1, N=85, 151 the VLSI implementation is done and for the case N mod 3=0, N=21, 81, 147, the VLSI implementation is done where N is of odd length sequence. Comparison is done as shown in table 2 and table 3 between the previous work and this work. This method is efficient for larger filter taps.

Here, **α**is total number of multiplication operations and **β**is reduced number of multipliers.For N=151, the number of reduced multipliers are 25.Reduced power consumption and utilization are two additional benefits of the application of fast FIR algorithm and coefficient symmetry property.

Total power is sum of static power and design dynamic power. Utilization is the number of Look Up Tables (LUTs), Filp flops (FFs), Input/Output ports (IO), Global Buffer (BUFG), Look Up Tables Random Access Memory (LUTRAM).

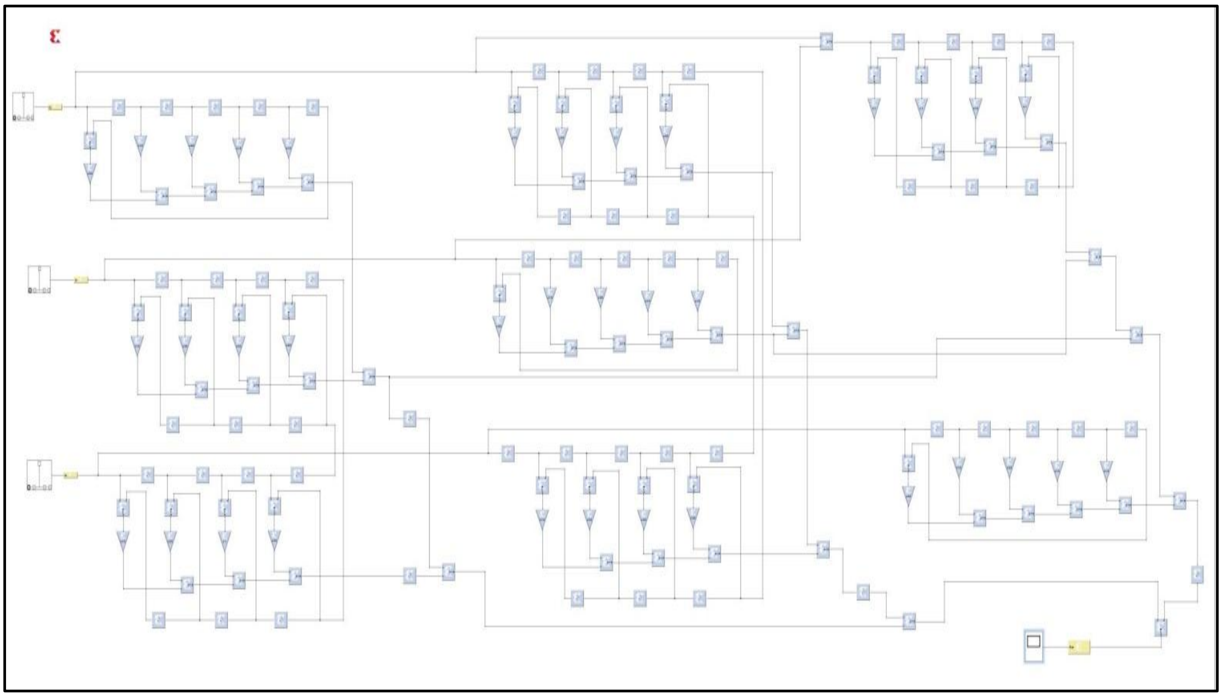

Figure 7: 3-parallel FIR filter after the application of modified FFA for odd sequence of N=25 (Nmod3=1)

N	Structures	Total Power (Watts)	Utilization (percentage)	Setup time (nano seconds)	Hold time (nano seconds)

16	Conventional Type-1 polyphase FIR filter	0.208	17.47	14.672	4.253
	Application of the coefficient symmetry property in a Type-1 polyphase FIR filter	0.191	17.06	12.034	3.776
96	Conventional Type-1 polyphase FIR filter	0.290	24.26	26.523	8.677
	Application of the coefficient symmetry property in a Type-1 polyphase FIR filter	0.247	22.66	25.912	8.600

Table 1 Comparison of polyphase FIR filter before and after applying coefficient symmetry for N=16 and 96.

N	Structures	α	Ɽ	Power (Watts)	Utilization (percentage)
21	Existed FFA [15]	30		0.382	18.43
	Modified FFA	29	1	0.382	18.42
81	Existed FFA [15]	109		0.519	21.70
	Modified FFA	108	1	0.519	21.68
147	Existed FFA [15]	197		0.689	25.48
	Modified FFA	196	1	0.506	25.42

Table 2 Comparing the performance of 3-Parallel FIR Filters for odd length sequence of N(Nmod3=0).

N	Structures	α	Ɽ	Power (Watts)	Utilization (percentage)
25	Existed method [15]	39		0.39	18.46
	Modified FFA	35	4	0.39	18.43
85	Existed method [15]	129		0.532	22.14
	Modified FFA	115	14	0.508	21.90
151	Existed method [15]	228		0.690	25.98
	Modified FFA	203	25	0.648	25.51

Table 3 Comparing the performance of 3-Parallel FIR Filters for odd length sequence of N (Nmod3=1).

The total power consumption and area utilization is reduced with the application of coefficient symmetry property and fast FIR algorithm as observed from table 2 and table 3. Especially for N=147, the power consumption is reduced by 26% by using this modified FFA. And for N=151, the total number of multipliers are reduced by 25 and the total power consumption is reduced by 6% after applying coefficient symmetry and fast FIR algorithm.

In image processing application, smoothening and enhancing visual content involve applying 2D and 3D Finite Impulse Response (FIR) filters. Smoothing is achieved by reducing noise in the image, while enhancement involves improving overall image quality.

5.Conclusion

VLSI implementation of conventional type-1 polyphase FIR filters with the coefficient symmetry has been done and it's parameters including power consumption, area utilization, signal delay analysed. By applying this coefficient symmetry property, optimized filters are obtained. To further enhance the efficiency of our filtering process, the work has been extended to implement 3-parallel FIR filters that leverage the property of symmetry shared by coefficients as well as fast FIR algorithm, for two different cases. Performance improvement in the research is achieved through a combination of factors. Leveraging coefficient symmetry and the modified FFA technique optimizes filter designs for improved performance. Coefficient symmetry reduces computational complexity, while the modified FFA minimizes the number of multiplication operations, which are typically the most computationally intensive. The results underscore the suitability of the FFA approach, particularly when dealing with FIR filters featuring a larger number of taps. For N=151 and 147, there is more reduction in power consumption as well as reduction in area utilization when compared to smaller taps. In addition, image smoothening and image enhancement application using 2D and 3D FIR filter is executed.

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