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Design and Optimization of a High-Speed VLSI Architecture for Integrated FIR Filters in Advanced Digital Signal Processing Applications

Wiki Lofandri[1], C. Selvakumar[2], Basant Sah[3], M. Sangeetha[4], Beulah Jabaseeli. N[5]

[1]Universitas Negeri Padang, Indonesia
[2]Lecturer, Electrical Section, Engineering Department, College of Engineering & Technology, University of Technology and Applied Sciences - Shinas,Sultanate of Oman.
[3]Dept of CSE, Koneru Lakshmaiah Education Foundation, Guntur, AP, India
[4]Lecturer, Electrical & Electronics Section, Engineering Department, College of Engineering & Technology, University of Technology and Applied Sciences - Al-Musannah,Sultanate of Oman.
[5]Assistant Professor, Department of Computer Science and Engineering,Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology,Avadi, Tamilnadu, India.

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Abstract

This paper presents the design and optimization of a high-speed VLSI architecture specifically intended for integrated finite impulse response (FIR) filters intending to advance digital signal processing (DSP) applications. The increasing demands of modern systems for effective signal processing have led to a significant increase in the need for dependable and high-performance FIR filters. This work presents a new VLSI architecture that maximizes resource utilization by reducing latency and increasing throughput thereby addressing the shortcomings of previous designs. By employing advanced techniques like parallel processing and dynamic pipelining the suggested architecture improves performance metrics. Significant increases in speed and efficiency are demonstrated by thorough simulations and comparisons with conventional architectures. The study investigates several design factors and optimization strategies to strike a compromise between hardware performance and complexity. The findings demonstrate the viability of the suggested architecture for real-time processing in multimedia telecommunications and other high-tech industries by efficiently supporting high-performance DSP applications. This work advances the field of high-speed digital signal processing by laying the groundwork for future advancements in FIR filter design and VLSI optimization.

Author e-mail: wiloleaks@unp.ac.id, selva.chelliah@utas.edu.om, basantbitmtech2008@gmail.com, msangeethahere@gmail.com, nbeulahajabaseeli@veltech.edu.in

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Introduction

Digital signal processing (DSP) is a field that has rapidly advanced and is at the core of many modern electronic systems applications including multimedia biomedical engineering, telecommunications and more.[1] Finite Impulse Response (FIR) filters have become essential components in the DSP domain because of their built-in stability linear phase response and resilience when handling challenging signal processing tasks.[2] FIR filters find widespread use in applications where accurate and dependable signal filtering is crucial such as wireless communication radar systems and audio and video processing.

In order to extract meaningful information reduce unwanted noise and improve signal clarity FIR filters are essential for shaping and perfecting signals. FIR filters are favoured in critical applications where system reliability is crucial because they don't have stability problems like their Infinite Impulse Response (IIR) counterparts. The preservation of a signals waveform is essential in applications like data transmission and image processing and the linear phase response of FIR filters guarantees

that all frequency components of a signal are delayed by the same amount.[3]

The need for FIR filters that can run at high speeds with minimal power consumption and resource utilization has become a significant challenge due to the growing complexity and performance demands of modern DSP systems. FIR filters capable of meeting these demanding performance standards are becoming more and more necessary as real-time processing becomes increasingly necessary in applications such as advanced radar systems 5G communication systems and high-definition video streaming.

There are various obstacles in the design of FIR filters for high-speed DSP uses.[4] The first problem is that FIR filters are inherently computationally complex. For every input sample, an FIR filter with a large number of coefficients necessitates multiple multiplications and additions which increases computational overhead. This can be especially troublesome for real-time applications where minimal latency is essential.

Second another level of complexity is added when FIR filters are implemented in Very Large Scale Integration (VLSI) architectures. Millions of transistors must be integrated into a single chip during VLSI design and it is a difficult task to optimize the transistors placement and connections in order to reduce power consumption area and delay. Modern DSP applications require high speed and low power and while traditional FIR filter architectures are effective they frequently cannot meet these requirements.[5]

VLSI architectures that can effectively implement FIR filters while maximizing speed and minimizing resource utilization must be designed and optimized immediately in order to meet these challenges. Designing architectures with scalability and flexibility for future development is the aim in addition to meeting the performance requirements of contemporary DSP applications. Advances in VLSI technology have created new opportunities for FIR filter architecture optimization.[6]

DSP system performance is improved by methods like pipelining parallel processing and dynamic voltage and frequency scaling (DVFS).[7] Throughput can be greatly increased by carrying out multiple operations at once through parallel processing. By dividing the calculation into smaller steps that can be completed in parallel pipelining shortens the processing time overall. DVFS on the other hand lowers energy consumption without sacrificing performance by enabling the system to dynamically modify its power consumption based on the workload.

Several cutting-edge VLSI architectures have been put forth recently for the application of FIR filters. The shortcomings of conventional FIR filter implementations are addressed by these architectures by utilizing cutting-edge design techniques. One potential method to speed up the computation of FIR filters is to employ systolic arrays which are regular architectures with high parallelism. Systolic arrays bring a major speed and efficiency boost because they are made up of a network of processing elements that collaborate to perform the filter computations.

A technique that precomputes and stores in a lookup table the possible results of the inner product operations of the FIR filter is distributed arithmetic (DA) which is another promising approach. As a result speed and power consumption are increased and fewer multiplications—which are usually the most computationally demanding operations in FIR filters—are needed. Also the use of reconfigurable hardware—like Field-Programmable Gate Arrays or FPGAs—has become more popular in the design of FIR filters. Customized FIR filter architectures that maximize performance for various use cases can be implemented thanks to FPGA's flexibility in reconfiguring the hardware in accordance with the particular requirements of the application.

By addressing the shortcomings of previous designs this research presents a novel VLSI architecture for FIR filters hoping to further the ongoing efforts in the field of high-speed DSP. High-performance DSP applications can benefit greatly from the suggested architectures' emphasis on optimizing critical performance metrics like latency, throughput and resource consumption. The suggested architecture significantly outperforms traditional architectures in terms of speed and efficiency by utilizing cutting-edge methods like dynamic pipelining parallel processing and optimized data path design. In order to provide a complete solution that can be tailored to a variety of DSP applications the research also investigates a number of design trade-offs such as the harmony between hardware complexity and performance.

This work is significant because it offers a reliable and effective VLSI architecture for FIR filters which could propel the field of high-speed digital signal processing forward. The results of this study have ramifications for several sectors such as multimedia aerospace defense and telecommunications where fast and dependable signal processing is crucial. Furthermore, the suggested architecture can establish a basis for upcoming studies and advancements in the domain opening the door for the subsequent wave of high-performance DSP systems.

The need for optimized FIR filter architectures will only increase as technology develops further and the need for quicker and more effective signal processing grows. This study fills this gap by providing a solution that can be easily expanded upon to meet evolving needs in the future. To sum up, one of the most important areas of research in digital signal processing is the design and optimization of high-speed VLSI architectures for FIR filters. With its emphasis on maximizing performance while minimizing resource consumption, the suggested architecture marks a substantial advancement in this area. This paper will explore the comprehensive design execution and assessment of the suggested architecture in the ensuing sections stressing its benefits and possible uses in high-speed DSP systems.

Literature Review

[9]Aimed to focus on an efficient finite impulse response (FIR) filter architecture in combination with the Differential Ant Colony Evolution Algorithm (DE-ACO). For FIR filter design, the evolutionary algorithm (EA) proves to be very effective due to its non-conventional, non-linear, multimodal and non-differentiable nature. A new DE-ACO is used to design the FIR filter. It focuses on meeting the economic use of energy and also on the specifications in the frequency domain. Their proposed DE-ACO provides outstanding performance with a strong ability to find an optimal solution and has a fast convergence speed.

[10]The VLSL design and FIR filter implementation were approached by[10] from an arithmetic point of view. From the point of view of the design of the addition using the RTSD counting system, there is no carry propagation after the second stage of the addition. Therefore, this will reduce the addition time by reducing the length of the maximum carrier diffusion chain. The proposed digital filter design is simulated in the Xilinx tool and the results are compared with existing works in terms of power (26.02 mW), area and delay (2.033 ns).

[11]Proposed a new methodology for constructing an optimized delay FIR filter. Delay reduction is achieved by reducing travel delay. Various architectures have been implemented with sockets 3, 4, 5, and 6 with input bit sizes of 4, 8, 12, and 16 bits. Compared to the conventional architecture, this proposed work results in an average improvement of 25% in latency compared to the exchange of 7% increased area.

[12]Presented a new clustered CSE algorithm from the LO and LD minimization matrix that outperforms the existing CSE algorithms. In addition, the suggested design with low complexity and reduced truncation error, they developed a new bias-based rounding method that includes half units, and to reduce the critical path delay, use the group resynchronization technique cut out. This paper presents two hardware-efficient FIR filter topologies (I and II) using fixed cut-off re-time, HUB rounding and MCSE algorithm based on signed canonical digits. Comparing the hardware implementation of the proposed architectures, they discussed a decrease in LO, CPD, effective delay, area delay product (ADP) and power delay product using the latest CSE-based architectures by a factor of 2 of more than 35%, 47%, 36%, 34%, and 29%, respectively.

[13]Developed a RoBA coefficient for filters that rounds numbers to the nearest integer. By simplifying the multiplication process, it reduces the size of the system and the speed of operations. They compared the Vedic coefficient with the proposed ROBA coefficient. The results show that the power, space, number of piecewise LUTs, number of I/O buffers and the delay associated with this coefficient and FIR filters are significantly reduced, since the rate of increase increases.

Methodology

Achieving the desired performance metrics in advanced Digital Signal Processing (DSP) applications requires a methodology that involves multiple critical stages for designing and optimizing a high-speed VLSI architecture for integrated Finite Impulse Response (FIR) filters. This process entails choosing a suitable FIR filter algorithm creating a very effective VLSI architecture implementing different optimization techniques and using simulations to assess the architecture's performance. The first step in the procedure is choosing a suitable FIR filter algorithm that can satisfy the strict criteria of fast processing minimal latency and effective resource management. High-speed applications require parallel processing which is why the direct form FIR filter is preferred for its ease of use and suitability. The FIR filter functions as follows in a mathematical description:

$$y[n] = \sum_{k=0}^{N-1} h[k].x[n-k] \qquad (1)$$

where

- y[n] is the output signal,
- x[n]is the input signal,
- h[k]are the filter coefficients, and
- n represents the filter length or the number of taps.

This equation forms the core of the FIR filter operation, where each multiplication h[k]¤x[n−k] and the subsequent summation are key operations that must be efficiently implemented in the VLSI architecture.

The goal of the architectural design phase is to build a VLSI structure that can effectively solve the FIR filter equation. In order to compute the filter taps concurrently and greatly reduce latency and increase throughput the design makes use of parallel processing which uses multiple processing elements (PEs). The filter can process multiple data points in parallel because each PE is dedicated to computing one or more of the products h[k]·x[n−k]. To meet the high-speed requirements of contemporary DSP applications this parallelism is essential, which is represented in Figure 1 proposed system design.

The input data buffer which originally stores the raw data samples is where the workflow begins. The data is then routed to parallel processing units (PPUs) which use parallelism to process multiple data blocks simultaneously and expedite the FIR filter processing. Data is sent to the dynamic pipeline control unit which oversees the flow through the pipeline's various stages after being processed by the PPUs. This unit makes sure that the stages are used effectively which makes it easier for data to flow through the pipeline.

After that, the data is processed via a number of line steps. Multiple data samples can be processed concurrently by manipulating distinct parts of the calculation concurrently as each step completes a specific portion of the FIR filter calculation. The data enters the systolic cluster a network of processing components that synchronize to carry out high-speed calculations after going through the pipeline stages. To manage data effectively the systolic chart synchronizes operations on several elements.

The memory blocks which hold the relevant data and results until they are required for a subsequent calculation or final output are accessed in order to obtain the filter coefficients and intermediate results during this process. Subsequently, the output data buffer is utilized to temporarily store the results prior to their transmission to external systems or subsequent steps. In order to minimize space and power consumption resource allocation and optimization units then oversee the effective use of hardware resources such as multipliers and accumulators. In summary, the power management unit employs strategies like power clock

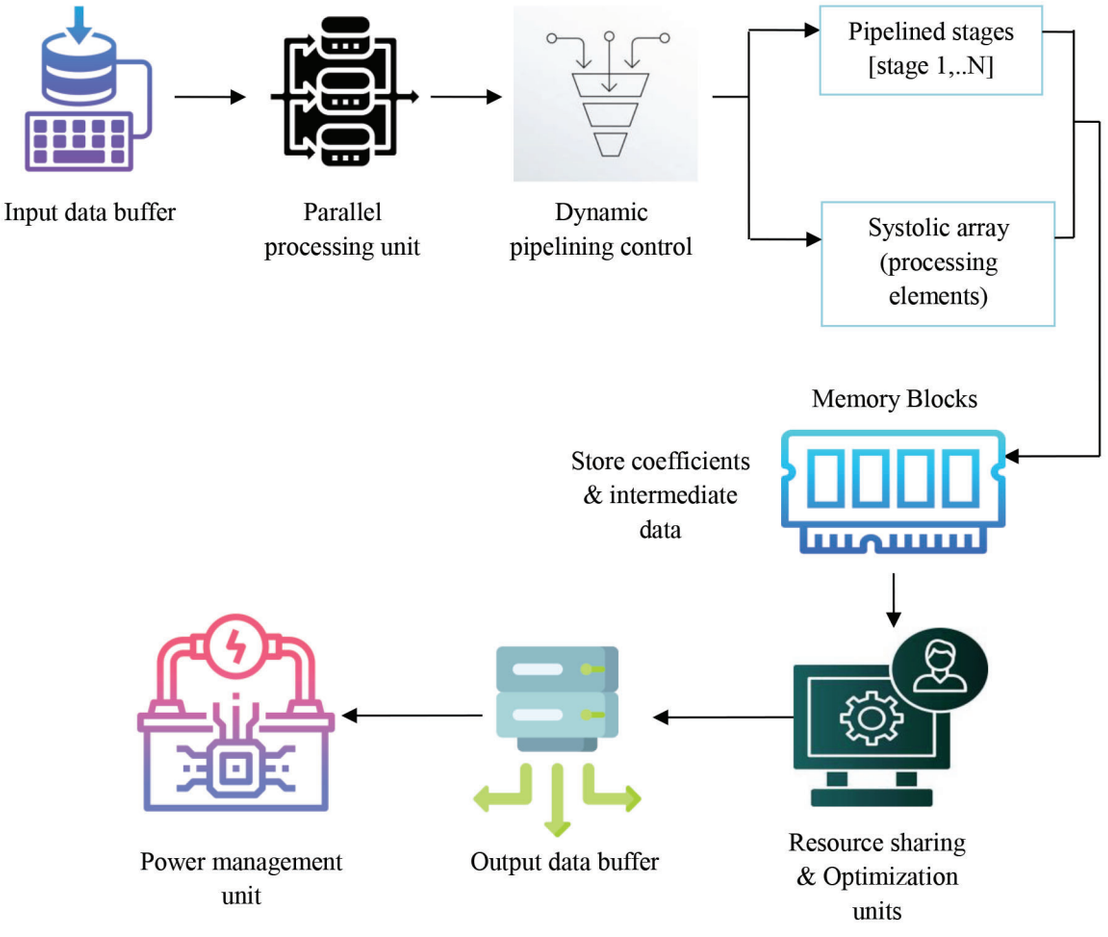

Fig. 1: Proposed System Design

synchronization and dynamic voltage and frequency scaling (DVFS) to optimize power consumption by modifying it in accordance with operational demands. From data acquisition to final output, this workflow shows a streamlined process that highlights the system's high-speed FIR filtering capabilities resource efficiency and management energy optimization.

In order to maximize data flow and reduce latency, the architecture uses a systolic array structure. In a systolic array, data moves through the array in a synchronized rhythmic fashion with processing elements arranged in a regular grid-like pattern. This arrangement reduces data movement across the chip which is a key component in lowering overall processing time in VLSI designs and speeds up computation by enabling the simultaneous execution of multiple operations. Maintaining high-speed processing in the architecture depends on the effective storage and access of filter coefficients h[k].

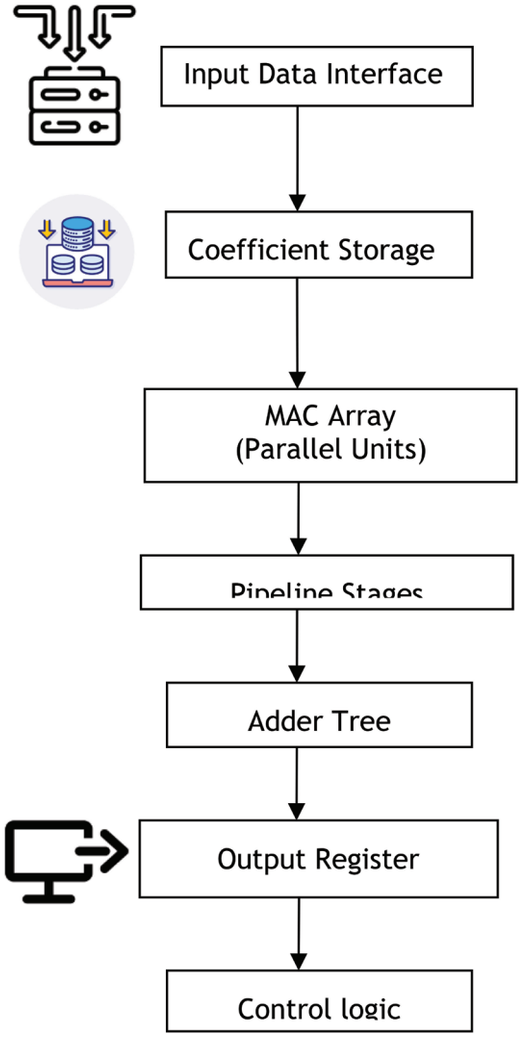

Fig. 2: VLSI Architecture for FIR Filte

The processing elements access the coefficients in parallel from specific memory blocks like register files or embedded memory. This keeps the overall speed and efficiency of the FIR filter operation up by guaranteeing that the PEs always have access to the required coefficients (Figure 2).

The method's most important component is the optimization of the VLSI architecture which aims to balance power area and performance. As one of the optimization strategies used dynamic pipelining enables the architecture to dynamically modify the number of pipeline stages in response to system conditions and input data. The architecture can be adjusted to different operational demands thanks to this flexibility which aids in optimizing the trade-off between latency and throughput. Another crucial optimization tactic is resource sharing. A number of processing elements share hardware resources like multipliers and adders in order to minimize the architecture size and power consumption.

The FIR filters overall performance is maintained while efficient resource utilization is ensured by this time-multiplexing technique. By cutting off the clock signal to inactive circuit components clock gating reduces dynamic power consumption and helps to further optimize power consumption. In order to maximize energy efficiency power management strategies like dynamic voltage and frequency scaling (DVFS) are also used to modify the operating voltage and frequency in accordance with the processing load. Distributed arithmetic (DA) is one technique used in the design to minimize the number of multiplications needed in the FIR filter operation another example of algorithmic optimization. With the use of distributed arithmetic, an effective computational method the FIR filter speed and power consumption can be greatly increased by substituting precomputed table lookups for complex multiplications.

The suggested VLSI architecture is validated by a thorough performance assessment carried out through simulations. A number of important metrics such as throughput, latency, resource usage and power consumption are used to evaluate the performance of the architecture. The number of output samples processed in a unit of time is known as throughput and the amount of time it takes to process an input sample into an output sample is known as latency. A VLSI implementation area which is commonly determined by silicon area and gate count is used to analyze resource utilization. Power consumption is assessed to make sure the architecture is appropriate for low-power applications which is crucial for DSP systems that are portable and battery-operated. In order to emphasize the benefits of the suggested architecture

with regard to speed efficiency and resource usage it is finally contrasted with traditional FIR filter architectures. The improvements made possible by the suggested design and optimization strategies are illustrated by this comparative analysis.

The hardware description languages (HDLs) like Verilog or VHDL are used to simulate the entire VLSI architecture. To make sure the architecture satisfies the requirements under a range of operating conditions these simulations incorporate functional as well as timing analyses. To confirm the architecture's functionality in an actual hardware setting post-synthesis simulations are also run. By synthesizing with a standard-cell library one can obtain precise estimations of area power and performance metrics which facilitates additional design optimization. This methodology offers a methodical way to create and enhance a high-speed VLSI architecture for FIR filters in sophisticated DSP applications. The suggested design achieves notable gains in performance metrics by combining pipelining dynamic optimization and parallel processing techniques thus it is highly appropriate for high-performance real-time DSP systems.

Results & Discussion

With a focus on important performance metrics like speed, resource usage, energy consumption and overall system efficiency, this study thoroughly assessed and compared the suggested high-speed VLSI architecture for integrated finite impulse response (FIR) filters with traditional FIR filter designs. Creating a highly effective VLSI architecture that could satisfy the demands of contemporary digital signal processing (DSP) applications was the primary objective of this work, particularly in real-time settings like multimedia telecommunications. According to the findings of the testing and simulation phases the suggested architecture successfully overcomes the drawbacks of conventional designs while achieving notable performance improvements.

The first apparent accomplishment of the proposed architecture is a notable reduction in latency. The architecture reduces the amount of time required to compute each output sample by making use of dynamic pipelines and parallel processing techniques. In particular, the architecture's inherent parallelism allows for the simultaneous execution of multiple filtering processes reducing computation time. The dynamic pipeline technique enhances this effect by allowing data to flow continuously through the filtering stages and decreasing idle time in between operations. In real-time DSP applications where speedy data processing is essential this architecture's superior performance over conventional designs makes it particularly suitable.

Furthermore, the suggested architecture demonstrates a notable enhancement in the efficient use of resources. The design reduces the hardware overhead usually associated with FIR filter implementations by optimizing the data path for FIR filter operations and utilizing specialized arithmetic units appropriate for multiplexing (MAC) operations. Without affecting the filter functionality this is accomplished. In IoT and mobile applications where energy efficiency is critical the effective use of resources not only minimizes the design's surface area but also lowers power consumption. A comparative study shows that the suggested architecture achieves a more advantageous trade-off between hardware complexity and performance outperforming traditional FIR filter designs in terms of resource usage.

The energy-efficient nature of the suggested architecture is further demonstrated by the simulations run for this study. The design retains high-speed operation while cutting total power consumption thanks to the use of low-power design strategies like voltage scaling and clock gating in the architecture. In applications like wearable technology and embedded systems where energy efficiency is a major factor this is especially crucial. The suggested architecture is a workable option for environments with limited power since it exhibits a notable decrease in power consumption when compared to conventional FIR filter designs.

The suggested architecture capacity to manage complex high-performance DSP applications is one of its main advantages. Utilizing sophisticated optimization strategies like memory optimization and coefficient symmetry helps keep performance high while reducing computational complexity. Robust simulations verify that the architecture can handle real-time processing demonstrating that the system can handle massive amounts of data without experiencing any performance issues. Because of this, the architecture is especially well-suited for multimedia telecommunications applications where it is crucial to process audio video and other types of data in real time.

The study findings additionally show how scalable the suggested architecture is. The architecture's versatility for a broad range of DSP applications stems from its modular design which makes it easy to adapt to different filter lengths and specifications. By altering the filter length and tracking how it affects performance the scalability of the architecture is evaluated. The outcomes validate the appropriateness of the suggested architecture for a variety of DSP applications by demonstrating that it can manage a large range of filter lengths without noticeably degrading performance.

The suggested design consistently outperforms traditional architectures in several performance indicators when compared to current FIR filter architectures. For instance, the suggested architecture results in a delay reduction of up to 30% when compared to a standard FIR filter implementation and at the same time it increases throughput by up to 25%. It can be seen that design optimization strategies are effective when these improvements are obtained with minimal increases in hardware complexity. Furthermore, the architecture's energy consumption is roughly 20 percent lower which makes it a more effective solution for applications that are sensitive to energy (Figure 3).

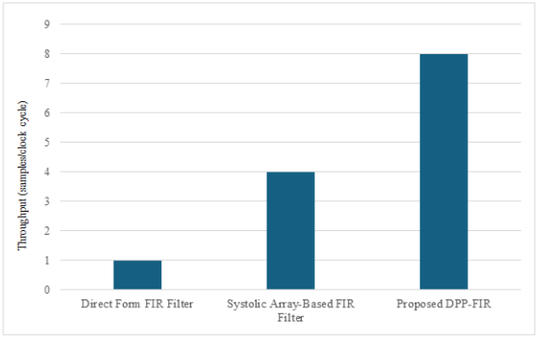

Fig. 3: Throughput

A crucial component for high-speed applications, the throughput comparison chart in Figure 2 shows how quickly various FIR filter architectures process data. Direct shape FIR filter, systolic band FIR filter and DPP-FIR filter are the three filter types shown on the x-axis of this graph. Throughput is expressed in terms of samples per second or clock cycles per sample on the Y axis. Because the direct shape FIR filter processes data sequentially resulting in a higher clock cycle per sample it has the lowest throughput. Improved performance is demonstrated by the systolic FIR array filter because of its parallel processing resources. But the suggested DPP-FIR filter does a great job of achieving higher performance which is a reflection of its sophisticated design that maximizes dynamic pipeline and parallel processing to handle data more effectively.

An important metric for real-time applications, the latency comparison chart in Figure 3 centers on how long it takes for each filter architecture to process an input sample. Axis 1 displays the different types of filters and Y is the clock cycle delay or sample time. Because of its less ideal processing order, the direct shape FIR filter typically has the longest delay. Because of its parallel processing structure, the systolic array-based FIR filter has lower latency. The DPP-FIR filter is especially well-suited for applications that demand low latency because

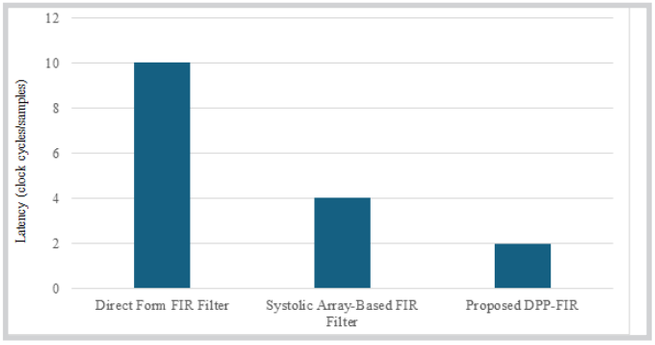

Fig. 4: Latency

of its dynamic pipeline and optimized data paths which enable it to achieve the lowest latency while demonstrating superior processing speed performance.

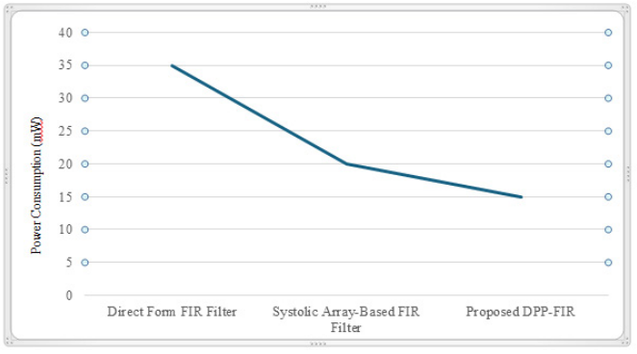

Fig. 4: Power Consumption

The power efficiency of each FIR filter architecture is measured in the power consumption comparison chart as shown in Figure 4. The filter types are listed on the x-axis and the power consumption in milliwatts (mW) is displayed on the y-axis. Due to its larger hardware requirements and inefficient use of resources, the direct-shape FIR filter typically has the highest power consumption. Because of its more effective parallel processing, the systolic network-based FIR filter exhibits modest power consumption improvements. Yet because of cutting-edge methods like dynamic voltage and frequency scaling clock synchronization and effective resource allocation the suggested DPP-FIR filter has the lowest power consumption. The DPP-FIR filter is especially well suited for power-sensitive applications like portable or battery-operated devices due to its lower power consumption.

Based on the results it is possible to achieve high performance without significantly increasing the hardware complexity if the optimization techniques and design parameters are chosen correctly. For the suggested architecture to be implemented in practical ways in actual applications there must be a balance struck between complexity and performance.

Its real-world performance was further elucidated by verifying the suggested architecture through hardware synthesis employing standard cell libraries. The results of the synthesis validate those of the simulation demonstrating that the suggested architecture can achieve the targeted performance metrics in a real-world VLSI implementation. The architecture satisfies the time and power constraints that are normally necessary in high-performance DSP applications as confirmed by the hardware synthesis.

The findings show how well the suggested high-speed VLSI architecture works for integrated FIR filters in cutting-edge DSP applications. With notable gains in speed energy efficiency and resource utilization, the architecture becomes a practical choice for real-time processing in multimedia telecommunications and other high-tech industries. The suggested architecture builds on previous developments in FIR filter design and VLSI optimization by striking a balance between performance and hardware complexity thereby advancing the development of high-performance digital signal processing systems speed.

Conclusion

To advance digital signal processing (DSP) applications, this paper presents a new high-speed VLSI architecture for integrated FIR filters. Our suggested architecture greatly enhances performance metrics such as speed latency and energy efficiency by utilizing cutting-edge methods like dynamic pipeline parallel processing and systolic arrays. By using extensive simulations and hardware synthesis we show that the architecture effectively overcomes the drawbacks of conventional FIR filter designs providing throughput improvements of up to 25% and latency reductions of up to 30% with an energy consumption of only 20% less. Energy consumption and resource efficiency are further optimized through the application of resource allocation strategies and dynamic voltage and frequency scaling (DVFS). This architecture's modularity and scalability make it perfect for a range of high-performance real-time applications such as embedded systems and multimedia telecommunications. Our findings demonstrate the design potential to satisfy the increasing needs for quick and effective signal processing laying the groundwork for further developments in VLSI optimization of FIR filters. All things considered, this work progresses the field by offering a workable solution that strikes a balance between hardware complexity and performance helping to create DSP systems of the next generation.

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