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Review

Enhancing Digital Signal Processing: Obstacles and Advancements in FPGA and ASIC Hardware Implementations

Md Rahatul Ashakin [a], Bayazid Hossain[b], Syed Mosaddik Hossain Ifty [c*]

[a]Department of Information Technology, Washington University of Science and Technology, USA
[b]Department of EEE, Barishal Engineering College, Bangladesh
[c]Department of EEE, Brac University, Bangladesh

Corresponding author: syedifty99@gmail.com

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ABSTRACT

This review study explores progress in digital signal processing (DSP) utilizing field-programmable gate arrays (FPGAs) and application-specific integrated circuits (ASICs). FPGAs provide adaptability and reconfigurability, rendering them appropriate for situations necessitating frequent enhancements. Engineers design ASICs to achieve maximum performance and efficiency in specific, consistent applications. The study addresses difficulties like optimizing computational efficiency, minimizing energy usage, improving algorithmic implementation, and overcoming resource limitations. Recent advancements in DSP hardware include AI integration, chip miniaturization, and enhanced synthesis tools. These technologies are revolutionizing DSP technology, improving machine learning applications, reducing power consumption, managing algorithmic complexity, optimizing resource allocation, and assuring scalability within hardware constraints. The study examines advancements in secure DSP hardware, sustainable chip technology, and the potential for hybrid quantum computing applications. The study underscores the necessity for ongoing research and innovation to tackle contemporary difficulties and improve the capabilities of DSP hardware across several industries, including telecommunications, healthcare, and automobiles.

1. Introduction

Putting needed digital signal processing (DSP) algorithms on specialized hardware platforms like Field-Programmable Gate Arrays (FPGAs) and Application-Specific Integrated Circuits (ASICs) is a big step forward in the field of DSP (Ashakin et al., 2024; Ifty et al., 2024). These platforms include the Fast Fourier Transform (FFT), Infinite Impulse Response (IIR) filters, and Finite Impulse Response (FIR) filters (Ifty et al., 2023a). An increasing demand for rapid, efficient, and adaptable processing in applications ranging from telecommunications to sophisticated medical imaging has propelled this transition (Bari et al., 2023; Sunny et al., 2021; Khatun et al., 2024; Moushumi et al., 2024). Contemporary computer systems confront an unparalleled challenge: the exponential surge of data produced by embedded electronic devices, nearing Exa-scale. As a result, hardware solutions like FPGAs and ASICs have become crucial tools for tailoring and enhancing

performance in specialized DSP applications (Ifty et al., 2023b).

Signal processing, a discipline that emerged from telecommunications, concentrates on the analysis, alteration, and synthesis of signals, including audio, visual data, and scientific measurements (Ashrafi et al., 2013; Chakma et al., 2022). Over the years, the domain of DSP has expanded, establishing itself as a fundamental technology across several industries, including healthcare, automotive, and consumer electronics (Knagge, 2022; Kuddus et al., 2022). The selection of hardware platform FPGA or ASIC profoundly influences the performance, adaptability, and cost-effectiveness of DSP implementations.

FPGAs and ASICs provide distinct benefits for DSP applications. FPGAs operate as a "digital canvas," providing programmability and reconfigurability. Their architecture facilitates swift adaptation, rendering them optimal for DSP applications that require flexibility and regular upgrades (Proakis, 2007). This versatility enables FPGAs to execute a diverse array of operations, from basic logic functions to intricate computations, which is especially advantageous during development phases or in applications requiring frequent modifications after deployment (Rodríguez-Andina et al., 2015). On the other hand, engineers design ASICs for specific, dependable applications that maintain their functionality even after manufacturing (Ashakin et al., 2024; Sazzad et al., 2024a). Embedded systems and high-volume consumer electronics, which priorities stability over flexibility, recognize ASICs for their efficiency and superior performance in executing high-volume, repeated DSP operations. Notwithstanding the evident advantages, the deployment of DSP algorithms on FPGAs and ASICs entails significant obstacles (Sheikh et al., 2021; Sazzad et al., 2023). This encompasses enhancing computing efficiency, regulating power consumption, guaranteeing real-time processing capabilities, and tackling algorithmic complexity, all while adhering to the limitations of each hardware platform's architecture (Tewksbury, 1996; Sunny et al., 2023; Sazzad et al., 2024b). Further difficulties emerge in choosing the optimal hardware to reconcile performance with cost, especially in power-sensitive or resource-constrained settings. These limits necessitate that developers meticulously evaluate the capabilities and limitations of each platform before selecting an ideal solution for DSP requirements (Uzun et al., 2005; Tufael et al., 2024).

This study intends to provide a comprehensive analysis of these difficulties and the technical innovations that have arisen in response. To figure out the best way to use FPGAs and ASICs to meet the growing needs of DSP applications, this paper looks at new developments, design strategies, and modern approaches. Through comparative analysis, the study assists practitioners in making strategic decisions among different platforms. It also examines prospective developments in the domain, including AI integration, enhanced chip technology, and innovative methodologies in hardware creation. This article is a resource for comprehending the present and future environment of DSP hardware, enabling developers and researchers to make educated decisions that correspond with the unique needs and goals of their applications.

2. Methodology & Techniques:

2.1 Frequently Used Digital Signal Processing Algorithms:

2.1.1 FFT (Fast Fourier Transform):

Digital signal processing methods commonly employ the Fast Fourier Transform (FFT) for spectrum analysis, signal compression, noise reduction, and frequency analysis. It serves a fundamental function in converting signals into the frequency domain, facilitating more efficient processing and analysis in applications from telecommunications to medical imaging (Knagge, 2022).

2.1.2 Digital Filters (Finite Impulse Response and Infinite Impulse Response)

We widely employ digital filters like finite impulse response (FIR) and infinite impulse response (IIR) filters for signal smoothing, noise attenuation, and data extraction. Because they are naturally stable and have linear phase properties, FIR filters work well in FPGA implementations, which need to have very precise control over signal phase for DSP applications (Ifty et al., 2024).

2.1.3 Convolution

In signal and image processing, convolution plays a crucial role in filtering and feature extraction. Its extensive use encompasses domains such as computer vision and telecommunications, facilitating the identification of pertinent elements inside signals and pictures (Ifty et al., 2024).

2.1.3 Field-Programmable Gate Arrays (FPGAs)

Field-programmable gate arrays (FPGAs) are versatile semiconductor devices consisting of an array of configurable logic blocks (CLBs) linked by programmable interconnections. Each CLB comprises fundamental elements such as look-up tables (LUTs) for logical operations, multiplexers, and flip-flops for data retention (Sheikh et al., 2021). Flexible interconnects connect these elements, enabling the FPGA to reconfigure for a variety of applications. Input/Output Blocks (IOBs) provide connections between the FPGA and external devices, enhancing its adaptability in practical applications (Ashakin et al., 2024). Hardware Description Languages (HDLs), such as VHDL or Verilog, configure FPGAs by defining the functions of configurable logic blocks (CLBs) and their interconnections (Knagge, 2022). The FPGA receives the synthesized HDL code as a configuration file (bitstream), which enables the device to execute complex DSP operations, from basic logic to complex computational functions (Ifty et al., 2024).

3. Application-Specific Integrated Circuits (ASICs)

Unlike FPGAs, which are reconfigurable, application-specific integrated circuits (ASICs) cater to specific functions. HDLs articulate ASIC designs irrevocably during the fabrication process,

permanently integrating the necessary logic gates to execute designated functions. This customization enables ASICs to achieve elevated performance, power efficiency, and compactness, making them suitable for applications with consistent, high-volume demands, such as embedded systems and consumer electronics (Knagge, 2022). Nonetheless, each functional alteration necessitates a comprehensive redesign and re-fabrication, rendering ASICs expensive and rigid for dynamic applications (Ashakin et al., 2024).

4. Progression and Growth

The advancements in the capabilities of both FPGAs and ASICs in recent years have facilitated increasingly complex DSP applications.

FPGAs offer increased logic density, enabling more complex designs and integrations on a single chip. Many modern FPGAs feature System-on-Chip (SoC) designs, which integrate programmable logic with fixed hardware components such as memory blocks, peripherals, and processors (such as ARM and RISC-V cores). This integration accommodates high-performance applications by delivering an all-encompassing solution in a singular device (Ashakin et al., 2024). Moreover, FPGAs now accommodate high-speed connection standards like PCIe Gen5, 5G, and various Ethernet protocols, enhancing their applicability in domains necessitating high-bandwidth and real-time computing, including telecommunications and data centres (Knagge, 2022).

Progress in semiconductor fabrication has enabled ASICs to reduce process nodes. These developments provide expedited processing, reduced power consumption, and enhanced capabilities within a small framework, crucial for portable and embedded devices. Application-specific integrated circuits (ASICs), tailored for artificial intelligence (AI) and machine learning (ML), are becoming more prevalent, with specialized cores for efficient neural network computation (Ashakin et al., 2024). Techniques such as 2.5D and 3D IC packaging augment ASIC performance by enabling the stacking of numerous dies within a single package, hence enhancing functionality without compromising form factor. These advancements are propelling ASIC usage in AI-intensive domains, such as autonomous systems, where efficient real-time processing is crucial (Knagge, 2022).

This methodological section outlines the fundamental DSP algorithms, FPGAs, and ASIC architectures, as well as new hardware innovations that are revolutionizing digital signal processing capabilities and facilitating enhanced performance, efficiency, and application variety in contemporary DSP implementations.

5. Current Advancements

Digital signal processing (DSP) hardware implementation has come a long way in terms of flexibility, efficiency, and computing power. This is especially true for field-programmable gate arrays (FPGAs) and application-specific integrated circuits (ASICs). These advancements cater to

the growing need for high-performance computing in sectors such as telecom, medical imaging, autonomous systems, and data centres (Knagge, 2022).

Recent improvements in FPGA technology have significantly improved their processing capacity. Contemporary FPGAs have enhanced logic density, elevated input/output (I/O) velocities, and integrated elements like specialized DSP blocks and high-speed transceivers. These enhancements allow FPGAs to execute intricate and computationally demanding DSP tasks with increased efficiency. Upgrades enhance applications like real-time video processing, sophisticated wireless communication protocols, and adaptive signal filtering (Ifty et al., 2024). The addition of System-on-Chip (SoC) architectures to FPGAs has made them more flexible by combining programmable logic with built-in processors, memory, and peripherals to meet all of your complex signal processing needs. Furthermore, FPGAs now accommodate high-speed connectivity protocols such as PCIe Gen 5, 5G, and advanced Ethernet standards, rendering them essential for high-throughput, real-time applications in communication systems and IoT (Ashakin et al., 2024).

The focus for ASICs has transitioned to enhanced integration and specialization. Contemporary ASICs integrate enhanced functionality into a singular chip, maximizing performance while minimizing power consumption and physical dimensions (Ifty et al., 2024). This efficiency is essential for high-volume applications including consumer electronics, cryptographic systems, and neural network computing, where speed, compactness, and energy efficiency are critical. Progress in semiconductor technology has facilitated the transition of ASICs to smaller process nodes, enhancing their performance and reducing power consumption (Knagge, 2022). Moreover, methodologies such as 2.5D and 3D IC packaging enable the integration of numerous dies onto a singular chip, enhancing performance without expanding the physical dimensions (Ashakin et al., 2024).

The advent of high-level synthesis (HLS) tools has revolutionized the design and development of FPGA and ASIC implementations. These technologies facilitate the construction of signal processing algorithms using higher-level programming languages, such as C++; hence, they greatly expedite development schedules and simplify testing and validation prior to hardware deployment. HLS methodologies simplify hardware design, facilitating the accessibility and expeditious market introduction of powerful DSP applications (Ifty et al., 2024).

The incorporation of artificial intelligence (AI) and machine learning (ML) algorithms into FPGA and ASIC systems signifies a pivotal domain of innovation. These methods necessitate substantial computing resources, and hardware implementations on FPGAs and ASICs have demonstrated encouraging outcomes regarding processing velocity and energy economy (Ifty et al., 2024). This connection is essential for applications necessitating real-time decision-making and analysis, including autonomous cars, intelligent cameras, and IoT devices. Domains that require both flexibility and high performance commonly utilize specialized ASIC designs, such as AI-optimized cores and FPGA-based AI accelerators (Ashakin et al., 2024).

Contemporary FPGA and ASIC systems for DSP applications illustrate the integration of robust, efficient, and adaptable hardware with cutting-edge design techniques. These developments not only tackle the increasing complexity of DSP tasks but also create new opportunities for applications across other sectors (Sheikh et al., 2021). AI, advances in chip technology, and the use of advanced design tools all show how quickly this field is growing, which is helping to create the next generation of signal processing solutions.

6. Analytical Evaluation and Comparison

6.1 Obstacles in Hardware Execution

Executing digital signal processing (DSP) algorithms on hardware platforms like Field-Programmable Gate Arrays (FPGAs) and Application-Specific Integrated Circuits (ASICs) entails several technical and practical obstacles:

6.1.1 Algorithmic Complexity

DSP algorithms may encompass complex mathematical calculations and repeated processes. Modifying these algorithms for hardware implementation necessitates meticulous attention to parallelism, resource allocation, and optimized device architectures (Knagge, 2022).

6.1.2 Resource Limitations

FPGAs and ASICs possess constraints regarding memory, input/output capabilities, and logic gates. Achieving optimal performance within these limits necessitates sophisticated optimization methods (Ashakin et al., 2024).

6.1.3 Energy Consumption

Hardware implementations must reconcile power efficiency with performance, especially in portable or energy-limited applications. Reducing energy consumption without compromising performance remains a significant challenge (Ifty et al., 2024).

6.1.4. Latency and Throughput

Attaining minimal latency and maximal throughput is essential in several DSP applications. Developing a technology that minimizes processing delays while maintaining accuracy is complex and requires innovative approaches (Sheikh et al., 2021).

6.1.5 Optimization of Algorithms

Adapting software algorithms for hardware necessitates comprehensive optimization, which includes alterations to data representations, architecture-specific improvements, and algorithmic tweaks (Ashakin et al., 2024).

6.1.6 Complexity of design and verification

As DSP algorithms advance in complexity, hardware designs get increasingly intricate. Ensuring accuracy and dependability necessitates thorough testing and validation, which can be resource-demanding (Sheikh et al., 2021).

6.1.7 Accelerated technological advancement:

Maintaining alignment with advancements in FPGA and ASIC technology while adeptly employing current tools presents an ongoing challenge for developers. The selection of the most suitable platform for a specific algorithm in light of rapid technological progress increases the intricacy (Ifty et al., 2024).

6.2 Execution Strategies

The selection between FPGA and ASIC for DSP implementations is contingent upon criteria like application requirements, manufacturing volume, performance objectives, and cost concerns. Each platform possesses distinct advantages and drawbacks (Ashakin et al., 2024).

6.2.1 FPGA-Based Implementations

6.2.1.1 Adaptability and Reconfigurability:

FPGAs are superior in applications necessitating frequent updates or algorithmic alterations. Their adaptability is advantageous throughout growth or in swiftly changing sectors. This flexibility results in higher power consumption and reduced speeds relative to ASICs (Knagge, 2022).

6.2.1.2 Pace of Development

High-Level Synthesis (HLS) tools facilitate FPGA programming using high-level languages, hence decreasing development time and rendering them appropriate for applications with stringent time-to-market requirements (Sheikh et al., 2021).

6.2.1.3 Cost-Efficiency for Low to Moderate Volume

FPGAs are more cost-effective for low- to medium-scale production as they obviate the necessity for costly bespoke chip fabrication (Ifty et al., 2024).

6.2.1.4 Energy Efficiency

Despite recent developments on FPGA power efficiency, they continue to consume more power than ASICs for comparable activities, rendering them less appropriate for power-sensitive applications (Ashakin et al., 2024).

6.2.1.5 Mapping hardware to algorithms

Efficiently translating algorithms onto FPGA hardware necessitates comprehension of data representations and accuracy optimization while utilizing the platform's advantages.

6.3 ASIC-Based Implementations

6.3.1. Enhancement of Performance

ASICs provide enhanced performance and energy efficiency for certain applications, frequently exceeding FPGAs in speed and accuracy once engineered (Ifty et al., 2024).

6.3.2 Economic Efficiency at Scale

Reduced per-unit costs make ASICs ideal for large-scale production, as they mitigate the substantial initial design and manufacturing expenses (Sheikh et al., 2021).

6.3.3 Restricted adaptability

ASICs do not possess the flexibility of FPGAs. Any alteration necessitates a comprehensive redesign, rendering them inappropriate for applications with dynamic algorithms (Knagge, 2022).

6.3.4 Resource Administration

Advanced synthesis technologies enhance resource allocation in ASIC designs by producing customized hardware blocks tailored to workloads (Sheikh et al., 2021).

6.3.5 Design and Validation

ASIC designs require thorough modelling and simulations for early validation. Formal verification methods enhance dependability and precision (Ashakin et al., 2024).

6.3.6 Comparative Examination

This research indicates that FPGAs are optimal for dynamic applications with changing needs, whereas ASICs are preferable for stable, high-performance, and cost-sensitive applications with substantial production numbers (Ashakin et al., 2024). Both platforms serve distinct functions in facilitating effective DSP deployments across various sectors.

7. Future Tracks

There are a lot of possible breakthroughs in the field that are changing the way digital signal processing (DSP) algorithms will be implemented on field-programmable gate arrays (FPGAs) *and application-specific integrated circuits (ASICs) in the future.*

7.1 Incorporation of Artificial Intelligence (AI) and Machine Learning (ML)

The integration of AI and ML algorithms into FPGA and ASIC platforms is a critical trend influencing the future of DSP technology. Artificial intelligence and machine learning tasks frequently need significant computational resources, and hardware solutions have demonstrated efficacy in fulfilling these requirements (Ashakin et al., 2024). AI applications widely employ FPGAs due to their versatility, which enables real-time modifications for neural network processing. Similarly, engineers design ASICs, which include AI-specific cores, to achieve optimal efficiency and performance in machine learning inference operations. We anticipate this trend to stimulate innovation in areas such as driverless cars, robots, and intelligent IoT gadgets (Knagge, 2022).

7.2 Progress in Semiconductor Technology

Ongoing advancements in semiconductor fabrication, in accordance with Moore's Law, are augmenting the functionalities of FPGAs and ASICs. The shift to lower process nodes facilitates increased transistor density, permitting more intricate designs and enhanced power efficiency. These developments are essential for next-generation DSP applications that require expedited processing and reduced energy consumption, particularly in data-intensive sectors such as telecommunications and medical imaging (Ifty et al., 2024).

7.3 Integration of Quantum Computing

The prospective amalgamation of quantum computing components with conventional FPGA and ASIC platforms may transform the boundaries of DSP capabilities. Quantum computing provides resolutions to intricate signal processing challenges that are now insurmountable with conventional computing (Ashakin et al., 2024). Preliminary investigations on hybrid architectures that integrate quantum computers with traditional hardware platforms may create new opportunities for applications including cryptography, secure communications, and sophisticated scientific research (Knagge, 2022).

7.4 Priorities Security

As signal processing applications proliferate in critical sectors like defense, telecom, and finance, the focus on hardware security will intensify. We anticipate that future FPGAs and ASICs will integrate sophisticated security features, such as encryption modules and safe boot methods, to address weaknesses in hardware-based DSP implementations (Ifty et al., 2024). This emphasis is crucial to guarantee resilient and dependable performance in progressively adverse conditions.

7.5 Sustainability

Environmental issues are prompting an emphasis on sustainability in hardware design and production (Sheikh et al., 2021). Future developments in FPGA and ASIC technology will

emphasize energy-efficient designs, minimal material usage, and environmentally sustainable production methods (Knagge, 2022). These initiatives will facilitate the increasing need for sustainable practices in sectors such as consumer electronics and automotive systems.

8. Conclusion

Using digital signal processing (DSP) algorithms on Field-Programmable Gate Arrays (FPGAs) and Application-Specific Integrated Circuits (ASICs) is an important and growing area of hardware engineering. FPGAs are characterized by their versatility and fast prototyping skills, which make them suitable for dynamic and developmental applications. Conversely, ASICs demonstrate superior performance, power efficiency, and cost-effectiveness for high-volume, reliable applications.

The selection between FPGAs and ASICs is contingent upon application-specific criteria, encompassing scalability, budget limitations, and performance objectives. FPGAs excel in applications necessitating adaptability and regular modifications, but ASICs prevail in situations that require optimal efficiency and rapid execution for static algorithms.

Future advancements in this domain will likely concentrate on the integration of artificial intelligence and machine learning, enhancement of chip manufacturing methods, and investigation of quantum computing integration. These developments, together with an increasing focus on security and sustainability, will allow both FPGAs and ASICs to attain unparalleled efficiency and adaptability. This evolving environment underscores the necessity of continuous research and innovation. By confronting the hurdles and seizing the chances offered by advancing technology, the hardware implementation of DSP algorithms will persist in broadening its influence, enhancing sectors such as telecommunications, healthcare, automotive, and others. The future of DSP hardware is exciting, offering enhanced performance and transformational applications.

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Author Contribution
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A statement of conflicting interests

The authors declare that none of the work reported in this study could have been impacted by any known competing financial interests or personal relationships.

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