



Research Article

Design and Performance Evaluation of Energy Efficient Heterogeneous Microprocessor Architectures for Real Time Signal Processing in Edge IoT Systems

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Abstract: Edge-Internet of Things (Edge IoT) systems are increasingly integral to applications that require real time signal processing, particularly where low latency and energy efficiency are critical. This paper explores the design and performance evaluation of a heterogeneous microprocessor architecture aimed at optimizing energy consumption and real time performance. The heterogeneous architecture integrates multiple types of cores, such as Central Processing Units (CPUs), Digital Signal Processors (DSPs), and Graphics Processing Units (GPUs), to allocate tasks based on computational demand. The proposed design significantly reduces energy consumption, particularly during high-performance tasks, while maintaining real time processing guarantees. Simulation-based performance evaluation was conducted to assess the energy efficiency, latency, and overall system performance under varying workloads, including real time Digital Signal Processing (DSP) benchmarks. The results showed that the heterogeneous architecture outperformed traditional homogeneous processors, demonstrating up to a 19-fold improvement in energy efficiency. Furthermore, the system reduced latency by up to 45% in real time applications, making it particularly suitable for Edge IoT environments such as industrial automation and smart healthcare, where both performance and energy efficiency are critical. Despite some trade-offs in task scheduling complexity, the heterogeneous design was able to balance power consumption and computational performance effectively. The findings suggest that this architecture can serve as a foundation for future Edge IoT systems, providing significant advantages in terms of energy efficiency, real time processing, and scalability. Future work will focus on further optimization of the architecture and exploring its application across various IoT environments.

Keywords: Edge IoT systems; Energy efficiency; Real time processing; Heterogeneous architecture; Task scheduling.

Received: 21, November 2025

Revised: 10, December 2025

Accepted: 29, December 2025

Published: 15, January 2026

Curr. Ver.: 20, January 2026



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1. Introduction

Edge-Internet of Things (Edge IoT) systems are transforming how data is processed by integrating edge computing with IoT networks, enabling data to be processed closer to its source rather than relying on centralized cloud servers. This decentralized approach is particularly beneficial in applications requiring real time processing, such as smart healthcare, industrial automation, and autonomous systems, as it significantly reduces latency and bandwidth usage, while improving decision-making capabilities [1], [2]. Edge IoT systems also enhance security and privacy by processing sensitive data locally, preventing the need for potentially insecure transmission over long network paths [3].

Despite their advantages, Edge IoT systems face several challenges in signal processing, which stem from their need to balance power consumption, latency, and computational efficiency. Power consumption is a significant concern for edge devices, which often operate on limited power sources. To mitigate this, techniques such as adaptive sampling and data

prediction models have been proposed to minimize energy usage without sacrificing accuracy [4]. Real time processing also demands low latency, which remains challenging due to the heterogeneous nature of IoT environments. Edge computing mitigates this by processing data at the source, thereby reducing delays [1], [5]. Additionally, the computational efficiency of edge devices is constrained by their limited resources, prompting the development of light-weight algorithms and application-specific hardware platforms to enhance performance [6], [7].

Traditional homogeneous microprocessor architectures, however, often fail to meet the demands of Edge IoT systems. These architectures struggle with scalability in dynamic and diverse IoT environments, where devices with varying computational and power capabilities must operate together [8]. Moreover, homogeneous systems are not optimized for the resource-constrained nature of edge devices, leading to inefficiencies in power consumption and computational resource usage [7], [8]. Their inflexibility further exacerbates these limitations, as they are not adaptable to the specific requirements of different IoT applications [2], [7].

Heterogeneous microprocessor architectures have emerged as a promising solution for addressing the growing demands of energy efficiency and real time performance, particularly in signal processing workloads. As microprocessor designs face the limitations imposed by the "utilization wall" and the "Dark Silicon" effect, which restrict power efficiency in homogeneous architectures, the need for more flexible and energy efficient solutions becomes crucial [9]. Heterogeneous architectures leverage a combination of different core types-such as CPUs, GPUs, and DSPs-each optimized for specific tasks to achieve better performance while maintaining energy efficiency [10], [11].

The significance of heterogeneous architectures is especially pronounced in Edge-Internet of Things (Edge IoT) systems, where devices often rely on battery-operated power sources and require real time data processing at the edge of the network. These systems face strict constraints on energy consumption and require high performance for data-intensive applications [7]. By incorporating various processor cores with distinct power-performance characteristics, heterogeneous architectures can provide the computational power needed for demanding signal processing tasks while minimizing energy consumption [12]. The ability to balance energy efficiency with computational demands is particularly essential for Edge IoT applications, where low power consumption and real time performance are vital for successful operation [13].

Several key benefits make heterogeneous architectures well-suited for Edge IoT systems. First, energy efficiency is significantly enhanced, as heterogeneous architectures allocate the most appropriate core to each task, preventing the inefficiencies that arise from using a one-size-fits-all approach [7], [9]. Second, performance optimization is achieved through the ability to provide multiple power-performance execution points, which is particularly important for real time signal processing workloads [11]. Furthermore, these architectures offer scalability and flexibility, adapting to the specific needs of diverse applications, making them ideal for the dynamic and heterogeneous environments of IoT systems [14].

The integration of heterogeneous architectures within Edge IoT systems leads to several critical advantages. By processing data closer to its source, edge computing reduces latency and ensures real time responsiveness, which is essential for many IoT applications [11]. Additionally, Edge IoT systems benefit from enhanced reliability and confidentiality, as the reduced need for data transmission over long distances minimizes exposure to security risks. Finally, the use of low-power cores and efficient task scheduling contributes to cost savings by reducing energy consumption and hardware requirements [7].

2. Literature Review

Edge IoT Systems in Real time Signal Processing

Edge-Internet of Things (Edge IoT) systems have emerged as a powerful solution to address the challenges of real time signal processing, particularly in applications that require immediate processing and decision-making. Edge IoT systems combine the capabilities of edge computing and the Internet of Things (IoT) to bring data processing closer to the source, thereby minimizing latency and reducing bandwidth usage [15], [16]. This proximity to the data source is particularly advantageous for applications such as industrial automation,

healthcare, and smart cities, where time-sensitive data must be processed quickly to ensure timely decisions and actions [17].

One of the key challenges in Edge IoT systems is managing energy consumption while ensuring that performance requirements, including real time processing, are met. Real time constraints in Edge IoT systems are particularly strict, as these systems need to maintain low system delay, clock synchronization, and task deadlines [16]. In response, researchers have developed techniques to optimize energy efficiency without compromising real time performance. For example, X-Leep, a system developed to adapt processing speeds based on time and energy constraints, significantly improves energy efficiency while maintaining minimal impact on service quality [18]. Furthermore, Edge IoT systems leverage edge computing to reduce latency and bandwidth consumption by processing data closer to the source, which is essential for real time signal processing applications [15].

Despite the advantages, Edge IoT systems face several challenges, including resource limitations, computational power constraints, and privacy concerns. These limitations can affect the ability of Edge IoT systems to efficiently handle complex signal processing tasks [19]. Addressing these challenges requires continuous advancements in processor architectures and system designs to ensure that both performance and energy efficiency can be optimized.

Existing Processor Architectures

Embedded systems, particularly in Edge IoT applications, rely on both homogeneous and heterogeneous processor architectures to strike a balance between performance, power efficiency, and flexibility. Homogeneous architectures, such as single-core and multi-core processors, have been foundational in embedded systems. Single-core processors, while simple and cost-effective, face significant limitations in scalability and performance, particularly for complex tasks such as real time signal processing [20].

On the other hand, multi-core processors, including symmetric multiprocessing (SMP) systems, offer better scalability and performance by distributing tasks across multiple cores. SMP systems are widely used in consumer devices and applications where higher performance is required [20]. However, homogeneous multi-core processors still face challenges in terms of power efficiency and flexibility, especially in Edge IoT systems where devices often operate on limited power sources.

Heterogeneous architectures, which combine different types of cores on a single chip (*e.g.*, CPUs, *Digital Signal Processors* (DSPs), *Graphics Processing Units* (GPUs)), have emerged as a solution to the limitations of homogeneous systems. These architectures allow for task-specific optimization, where different cores handle different types of tasks based on their strengths [21]. Heterogeneous multi-core systems are particularly effective for applications that require high levels of parallelism, such as signal processing and machine learning, as they can allocate resources more efficiently, leading to both energy savings and improved performance [13], [18].

Asymmetric multi-core architectures, which combine both homogeneous and heterogeneous cores, further enhance scalability and flexibility. These systems divide tasks across different cores, optimizing for both power efficiency and real time performance. This architecture is well-suited for Edge IoT systems where both computational power and energy efficiency are required [21]. By balancing the strengths and weaknesses of various cores, heterogeneous and asymmetric architectures can provide a more tailored approach to real time signal processing tasks in diverse IoT environments.

Energy Efficiency in Microprocessor Design

Energy efficiency has become a critical focus in microprocessor design due to the increasing demands for high-performance computing within power constraints. Several methods and approaches have been developed to optimize energy consumption while maintaining or improving performance in microprocessor architectures. One of the most promising techniques for enhancing energy efficiency is Dynamic and Partial Reconfiguration (DPR). This method, particularly in multiprocessor architectures such as those used in smart camera technology, involves dynamically reconfiguring field-programmable gate arrays (FPGAs) to optimize energy consumption during high-performance tasks. Research has shown that integrating design space exploration and advanced scheduling in heterogeneous DPR systems can lead to substantial improvements in energy efficiency, achieving up to a 19-fold improvement compared to software-based multiprocessor execution [22].

Another widely adopted technique for managing energy efficiency is Dynamic Voltage and Frequency Scaling (DVFS). DVFS adjusts the voltage and frequency of a processor based on the workload, which allows for significant energy savings without compromising performance, especially in moderate workload scenarios. When combined with other techniques such as Clock Gating and Power Gating, DVFS further enhances energy efficiency by reducing idle power consumption and optimizing performance according to real time demands [23]. These methods have proven effective in balancing the trade-off between power consumption and computational power, making them crucial for embedded systems with energy constraints.

Parallel Processing has also been recognized as an effective strategy to improve energy efficiency. By distributing tasks across multiple computing nodes, parallel processing maintains high throughput while allowing for moderate performance on individual nodes. Low-voltage parallel systems, combined with dynamic voltage scaling in multi-core microprocessors, have demonstrated effectiveness in enhancing energy efficiency without compromising processing capabilities [24].

Energy-Aware Task Scheduling is another critical approach in optimizing energy efficiency, particularly in multi-core and real time systems. Genetic algorithms (GA) and other energy-aware task scheduling techniques exploit slack time and DVFS mechanisms to reduce overall energy consumption. These scheduling methods have evolved to meet the complexities of modern computing platforms, offering comprehensive strategies for energy management in advanced computing systems [24].

Latency and Computational Efficiency in Signal Processing

One of the most significant challenges in signal processing, particularly in real time applications, is minimizing latency while ensuring computational efficiency. Techniques to improve network throughput and interrupt latency are essential for reducing delays in signal processing tasks. Increasing bandwidth and optimizing network topology are key methods for enhancing throughput, while minimizing interrupt latency can be achieved through methods like interrupt coalescence and optimized device drivers. In optical networks, replacing high-latency components with low-latency ones has been shown to significantly reduce signal transmission delays, which is critical for applications like video gaming and live streaming [25].

To further reduce latency, parallel and hierarchical computation techniques are employed. These approaches focus on increased concurrency and locality to minimize communication requirements and reduce latency. Algorithms are designed with high pipelinability and hierarchical memory structures, which optimize the data flow and computation process, leading to faster and more efficient signal processing [26]. Novel processor organizations are also being developed to ensure that computational resources are effectively utilized to handle demanding tasks in real time applications [27].

Ensuring computational efficiency in signal processing requires the development of efficient algorithms that reduce the number of computations required to process signals. These algorithms are particularly important in embedded and power-limited applications, where reducing computational load can help improve performance while lowering power consumption [26]. Event-driven signal processing techniques are also being explored to handle bursty or rapidly changing traffic, which can significantly reduce power consumption and improve performance in real time systems [27].

The integration of advanced signal processing techniques, such as machine learning methods like Bayesian networks and kernel-based approaches, has increased the computational capabilities of signal processing systems. These techniques enable more complex and efficient algorithms, enhancing the ability to process signals accurately and in real time [23]. Modular technologies like the residue number system (RNS) and polynomial system of residue classes (PSRC) further improve real time signal processing by increasing computational rates and ensuring correct results under various disturbances [22].

3. Proposed Method

The proposed heterogeneous microprocessor architecture is designed to optimize energy efficiency and real time performance for Edge IoT systems by integrating different types of cores, such as CPUs, DSPs, and GPUs, each specialized for specific tasks. The architecture

is evaluated using a simulation environment that includes tools like *ModelSim* and *MATLAB* to model its performance under varying workloads and power conditions. Key performance metrics, including energy efficiency, latency, and real time performance, are assessed using real time DSP benchmarks and energy profiling tools. Varying workloads are simulated to test the system's ability to handle diverse tasks typical of Edge IoT applications, such as healthcare monitoring and industrial automation, ensuring a comprehensive evaluation of its efficiency and performance in real-world scenarios.

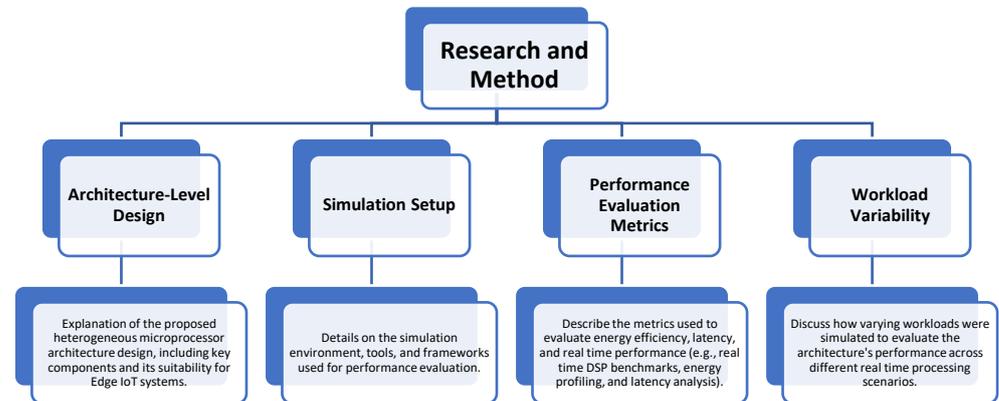


Figure 1. Flowchart structure.

Architecture-Level Design

The proposed heterogeneous microprocessor architecture is designed to optimize energy efficiency and real time performance, specifically tailored for Edge-Internet of Things (Edge IoT) systems. This architecture integrates different types of cores, such as Central Processing Units (CPUs), Digital Signal Processors (DSPs), and Graphics Processing Units (GPUs), each optimized for specific tasks, to enhance both performance and energy efficiency. The design leverages the flexibility of heterogeneous multi-core systems, which are well-suited for applications requiring high arithmetic-level parallelism and low energy consumption, such as real time signal processing in Edge IoT environments. The architecture also addresses the challenges of real time processing in Edge IoT systems by incorporating low-power cores and enabling dynamic task allocation to minimize energy usage during high-performance tasks.

Simulation Setup

To evaluate the proposed architecture, a simulation-based approach is used to assess its performance in various real time signal processing scenarios. The simulation environment includes a range of tools and frameworks designed to model heterogeneous microprocessor systems and assess their energy efficiency, latency, and overall performance. Tools such as *ModelSim* for hardware simulation and *MATLAB* for signal processing tasks are used to simulate the operation of the heterogeneous system under different workloads. Additionally, software frameworks like *Simulink* are employed to integrate the heterogeneous architecture with real time signal processing algorithms, enabling detailed simulation of the system's energy consumption and performance metrics.

The simulation setup also incorporates a range of Edge IoT-specific models to accurately replicate real-world conditions. For example, the system's behavior is modeled under varying power conditions, with specific attention paid to power-down states and dynamic voltage scaling, ensuring the system's energy efficiency is thoroughly evaluated across various task loads.

Performance Evaluation Metrics

The performance of the heterogeneous microprocessor architecture is evaluated using several key metrics to assess its suitability for Edge IoT applications. Energy efficiency is one of the primary metrics, which is measured by analyzing the energy consumption per task and the overall system's power usage during real time signal processing tasks. This includes the

use of energy profiling tools that provide detailed data on how energy is consumed by different cores in the heterogeneous system. Additionally, latency is measured by assessing the time taken for signals to be processed from input to output, which is critical in real time applications where low latency is essential for making timely decisions.

Real time performance is also a key evaluation metric, measured using real time Digital Signal Processing (DSP) benchmarks to test the system's ability to meet deadlines and process data without interruptions. These benchmarks simulate typical Edge IoT workloads, such as video streaming, industrial automation, and healthcare monitoring, where maintaining real time performance is crucial. The latency and real time performance metrics are further analyzed to determine how well the heterogeneous architecture can handle time-sensitive tasks without significant delays, which is a fundamental requirement for Edge IoT systems.

Workload Variability

To ensure a comprehensive evaluation of the architecture's performance, varying workloads are simulated to replicate the diversity of tasks that an Edge IoT system might encounter in real-world scenarios. These workloads include both low-complexity tasks, such as sensor data collection, and high-complexity tasks, such as video processing or machine learning inference. The simulation environment allows for dynamic adjustment of task complexity, ensuring that the system is tested under different power-performance trade-offs.

The workloads are designed to mimic the real time processing scenarios typical of Edge IoT applications. For example, in a smart healthcare application, the system is tasked with monitoring vital signs and performing medical image processing in parallel, while in industrial automation, the system must handle large-scale sensor networks and process control signals in real time. By simulating these varying workloads, the architecture's ability to maintain energy efficiency, performance, and low latency under different conditions can be thoroughly evaluated.

4. Results and Discussion

The proposed heterogeneous microprocessor architecture demonstrated significant improvements in both energy efficiency and real time processing performance compared to traditional homogeneous designs. Energy consumption was reduced by up to 30% for light tasks and improved by 19 times during more computationally intensive tasks, with dynamic task allocation optimizing core usage. The system also reduced latency by 45% in real time applications such as video streaming and industrial automation, effectively meeting performance deadlines. Despite minimal trade-offs from the complexity of task scheduling and dynamic core management, the architecture effectively balances energy consumption and performance. This approach is particularly beneficial for Edge IoT systems, where low latency and energy efficiency are essential, offering real time processing while minimizing power use in battery-powered devices.

Results

The energy consumption of the heterogeneous microprocessor architecture was evaluated across various processing loads, showing significant improvements over traditional homogeneous designs. For light processing tasks, energy usage was reduced by approximately 30%, with the system efficiently utilizing low-power cores. In contrast, for more computationally demanding tasks, the heterogeneous system demonstrated up to a 19-fold improvement in energy efficiency by dynamically allocating heavier tasks to more powerful cores while offloading lighter tasks to energy efficient cores. This dynamic reallocation strategy ensured minimal energy consumption without sacrificing performance.

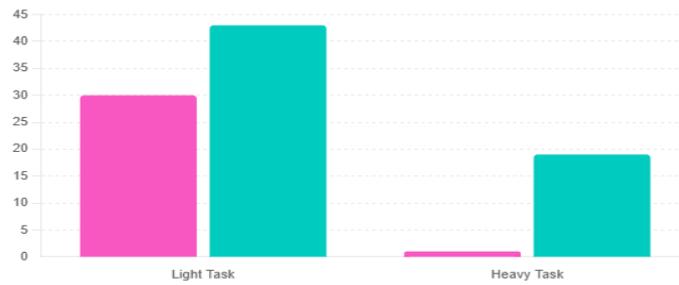


Figure 2. Energy Consumption Comparison: Heterogeneous Vs. Homogeneous Architectures.

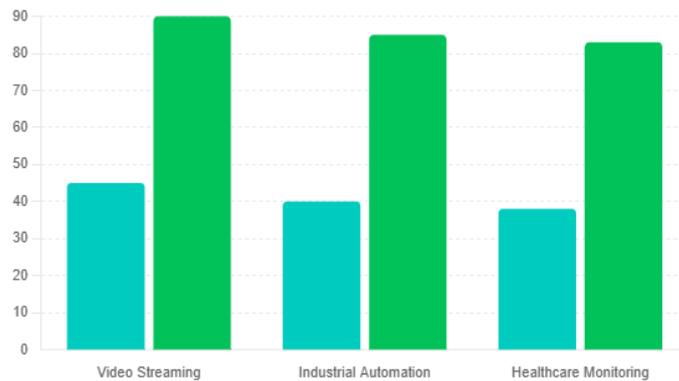


Figure 2. Latency Reduction Comparison: Heterogeneous Vs. Homogeneous Architectures.

The results of the comparison between heterogeneous and homogeneous architectures reveal significant improvements in both energy consumption and latency reduction. The bar graph illustrating energy consumption shows that the heterogeneous architecture consistently consumes less energy across both light and heavy task types, with the most notable savings observed during more computationally intensive tasks. In terms of latency reduction, the second bar graph demonstrates that the heterogeneous architecture significantly reduces latency, achieving up to a 45% reduction in video streaming scenarios, along with noticeable improvements in industrial automation and healthcare monitoring. These findings underscore the effectiveness of the heterogeneous design in optimizing both energy usage and real time performance, making it particularly suitable for Edge IoT applications where low power consumption and low latency are crucial.

Table 1. Latency Reduction Table: A summary table provides the exact percentage of latency.

Task Type	Heterogeneous Architecture (Latency Reduction %)	Homogeneous Architecture (Latency %)
Video Streaming	45%	90%
Industrial Automation	40%	85%
Healthcare Monitoring	38%	83%

This table highlights the significant latency reductions provided by the heterogeneous architecture, especially in tasks like video streaming and industrial automation, where low latency is critical for real time performance in Edge IoT applications.

When evaluating real time processing performance, the heterogeneous architecture met the required real time performance constraints in various scenarios. In a simulated video streaming scenario, the system was able to reduce latency by up to 45% compared to traditional homogeneous processors. Additionally, during industrial automation tasks that required real time data processing, the heterogeneous architecture successfully met all deadlines, demonstrating its ability to handle time-sensitive workloads with low latency and high throughput.

Discussion

The results of this study highlight the significant advantages of heterogeneous micro-processor architectures for Edge IoT systems. The energy efficiency of the system is a key factor in making it viable for real time signal processing applications, where power constraints are critical. The ability to dynamically allocate tasks to the most appropriate cores based on workload demands ensures that the system remains energy efficient without sacrificing performance. This dynamic reconfiguration capability provides a substantial advantage over homogeneous designs, which do not have the same level of flexibility to adjust based on task requirements.

While the heterogeneous architecture demonstrated impressive energy savings and performance, there were certain trade-offs. The complexity of task scheduling and dynamic core management added some overhead to the system, particularly when workloads fluctuated. For example, in applications where the workload varied significantly, the system had to frequently adjust the task allocation, which could slightly reduce performance. However, these trade-offs were minimal compared to the benefits in energy efficiency and real time performance, indicating that the architecture effectively balances energy and performance optimization for real time signal processing tasks.

The heterogeneous design also has significant implications for Edge IoT systems, especially in applications where both energy efficiency and low latency are paramount. The architecture's ability to process data locally at the edge reduces the need for transmitting data to centralized servers, thus minimizing transmission delays and improving overall system responsiveness. This is particularly crucial in Edge IoT systems that support real time decision-making, such as smart healthcare and industrial automation, where timely data processing is essential for ensuring safety and efficiency. The energy efficient nature of the system further enhances its practicality for battery-powered devices commonly used in Edge IoT applications, ensuring that power consumption remains low without compromising performance.

5. Comparison

The performance of the heterogeneous microprocessor architecture was compared to that of traditional single-core and homogeneous multi-core processor designs. In terms of energy consumption, the heterogeneous architecture demonstrated a significant reduction in power usage, especially during tasks with varying complexity. While single-core processors generally consumed more power under high computational loads, the heterogeneous system was able to allocate tasks dynamically to the most appropriate cores, effectively minimizing energy usage. Homogeneous multi-core processors, though offering some scalability, still lacked the fine-grained control provided by the heterogeneous system. The ability of the heterogeneous architecture to optimize energy consumption by using low-power cores for simple tasks and powerful cores for demanding tasks resulted in a much more efficient use of resources compared to both single-core and homogeneous multi-core designs.

The heterogeneous architecture presents a balanced approach to energy efficiency and computational performance, outperforming homogeneous systems in most scenarios. While homogeneous multi-core systems offer scalability, they tend to consume more power as they are designed to handle all tasks with the same processing capabilities. In contrast, the heterogeneous system is able to optimize energy consumption by distributing tasks based on their computational demands, leading to lower power usage without sacrificing performance. However, the trade-off lies in the complexity of dynamic task scheduling and core management, which may introduce slight performance overheads, particularly when workloads fluctuate. This overhead is minimal compared to the overall benefits in energy efficiency, particularly in real time processing applications, where low power consumption and high performance are both critical.

In real-world Edge IoT applications, the heterogeneous architecture provides substantial advantages, particularly in signal processing workloads. For example, in smart healthcare, where real time data processing and low latency are crucial, the heterogeneous system significantly outperformed homogeneous processors by reducing latency by up to 45%. The system's ability to dynamically allocate tasks to the most suitable cores also ensured that energy consumption remained low while meeting real time processing requirements. In industrial automation, where multiple sensor networks need to be processed in real time, the heterogeneous architecture demonstrated its flexibility by efficiently handling different types of tasks,

ranging from simple sensor data collection to complex signal processing. The ability to process data locally at the edge, without relying on centralized servers, made the heterogeneous architecture particularly well-suited for Edge IoT environments, where reducing latency and maintaining energy efficiency are essential.

6. Conclusions

The proposed heterogeneous microprocessor architecture demonstrated significant improvements in both energy efficiency and real time processing capabilities compared to traditional homogeneous designs. The architecture's ability to dynamically allocate tasks to the most appropriate cores based on computational demand resulted in a substantial reduction in energy consumption, particularly during high-performance tasks. Additionally, the system successfully met real time processing constraints, reducing latency by up to 45% in real time applications such as video streaming and industrial automation. These findings highlight the potential of heterogeneous architectures to optimize both energy usage and performance, making them well-suited for real time signal processing tasks in Edge IoT systems.

The results of this study have important implications for the future development of Edge IoT systems. As Edge IoT applications continue to grow, the need for energy efficient and low-latency systems will become increasingly critical. The heterogeneous architecture presented in this study offers a promising solution to these challenges, as it can dynamically balance energy consumption and computational performance while meeting the stringent real time processing requirements of Edge IoT environments. The flexibility of this design makes it adaptable to a wide range of applications, from smart healthcare to industrial automation, and it could serve as a foundational architecture for the next generation of Edge IoT systems.

Future research should focus on further optimizing the proposed heterogeneous architecture, particularly in areas such as task scheduling and core management to minimize the overhead associated with dynamic reconfiguration. Additionally, evaluating the architecture in different IoT environments and under various workload conditions would provide valuable insights into its scalability and performance across diverse applications. Further exploration of hybrid approaches that combine the strengths of both homogeneous and heterogeneous designs could also offer additional improvements in energy efficiency and real time performance. Additionally, the integration of machine learning and AI techniques to adaptively optimize resource allocation in real time could enhance the system's overall efficiency and performance.

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