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Design and Optimization of Low-Power VLSI Circuits for High-Performance Computing

Arti Sahu[1*], Prof. Saima Khan[1], Prof. Sandip Nemade [1], Dr. Divya jain [1]

[1] Technocrats Institute of technology, Bhopal

Abstract

The design and optimisation of low-power Very Large-Scale Integration (VLSI) circuits are the main topics of this study, which highlights how important these circuits are to raising the effectiveness of high-performance computing (HPC) systems. Power consumption is becoming a bigger problem as the need for HPC capabilities grows across industries, making it necessary to create circuits that can carry out intricate calculations with less energy consumption. This study examines the most recent approaches and strategies used in low-power VLSI design, including as dynamic frequency adjustment, voltage scaling, and sophisticated circuit topologies that enable notable power dissipation reductions without compromising performance. Additionally, the study explores the integration of power management techniques including sub-threshold operation and clock gating, which enable circuits to minimise consumption at lower activity levels while maintaining high performance levels under peak operational needs. The study also evaluates the trade-offs between operational speed, circuit complexity, and power efficiency with the goal of developing standards for low-power design in the future. As it relates to the continuous evolution of computational demands in a data-driven era, this research offers significant insights and contributions to the field by performing a comparative analysis of current low-power VLSI techniques used in HPC applications.

Keywords: *Advanced Gate Designs, Clock Gating, CNTFET Technology, Dynamic Voltage and Frequency Scaling (DVFS), Energy-Efficient Circuits, FinFET Technology, High-Performance Computing (HPC), Low-Power VLSI Design, Memory Optimization in VLSI, Power-Performance Trade-offs, Sub-Threshold Operation, TFET Technology.*

1. Introduction

Cloud computing, data analytics, scientific simulations, artificial intelligence (AI), and other fields have seen exponential growth in processing demand due to the quick development of high-performance computing (HPC). Higher processing power and faster computation are required as these applications continue to develop, increasing the demand for more potent computational systems. However, controlling power usage becomes more difficult as computational performance rises. Modern processors and systems are built on traditional VLSI (Very Large-Scale Integration) circuits, which frequently struggle to strike a balance between high performance and low power consumption. Because of this, low-power VLSI circuit design and optimization have become crucial components of contemporary computer systems, especially for HPC applications that need both computational and energy efficiency.

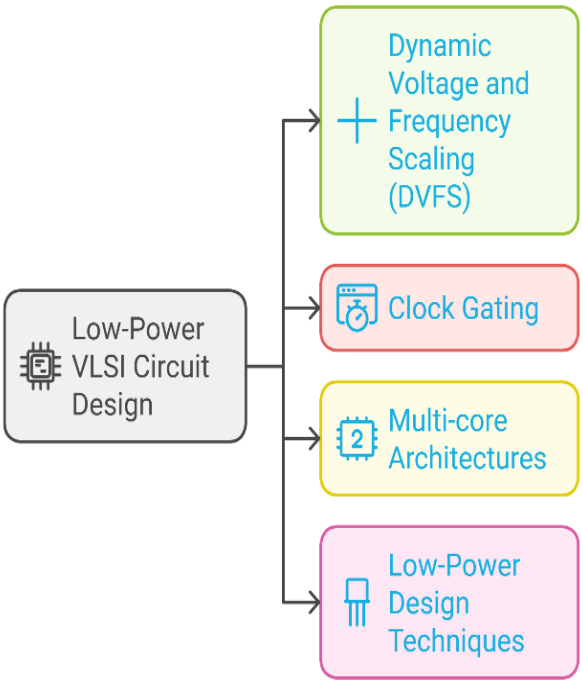


Fig. 1: Role of Low-Power VLSI Circuit Design

Because of the large number of transistors and high operating frequencies needed to achieve performance requirements, power consumption has become a crucial concern in the context of HPC systems. This has sparked worries about the operational costs of maintaining such high-performance devices as well as the effects on the environment. The development of low-power VLSI circuit designs that can reduce energy consumption while providing the computing capacity required to power these cutting-edge applications is therefore receiving more attention. Low-power design techniques are now essential to the effectiveness of massive data centers, supercomputers, and other computing infrastructure that serve as the foundation of HPC systems; they are no longer only a factor for portable electronics like laptops or smartphones.

Dynamic voltage and frequency scaling (DVFS) are a key method for lowering power consumption in VLSI circuits. In addition to helping to lower power consumption during periods of low workload, DVFS enables the system to dynamically modify the circuit's voltage and frequency in response to the computing workload. This allows the system to scale up at times of high-performance requirements. The adoption of sophisticated circuit topologies, such as adaptive body biassing (ABB) and multi-threshold CMOS (MTCMOS), which allow for large leakage power reductions without compromising performance, is another promising strategy for low-power VLSI design. By utilizing the intrinsic properties of the circuits and devices to function well at various power levels, these tactics seek to maximize power dissipation.

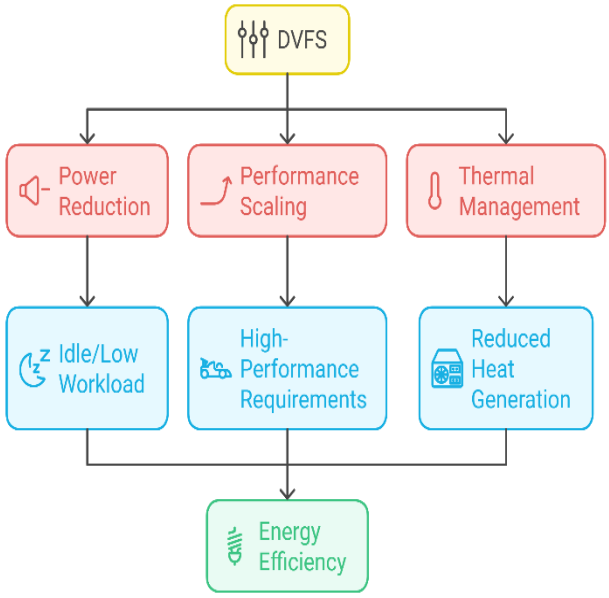


Fig. 2: Benefits of Dynamic voltage and frequency scaling (DVFS)

Sub-threshold operation is also becoming more popular as a method of lowering power usage even more. Circuits are run at voltages lower than the usual threshold voltage in sub-threshold operation, which drastically lowers power consumption at the expense of a minor decrease in speed. A crucial component of low-power VLSI design is the trade-off between speed and power, especially when creating circuits for systems with limited energy. Clock gating has gained popularity as a method of lowering dynamic power usage in addition to sub-threshold operating. Clock gating efficiently minimizes needless switching activity by selectively cutting off the clock signal to parts of the circuit that are not in use, which results in significant power savings.

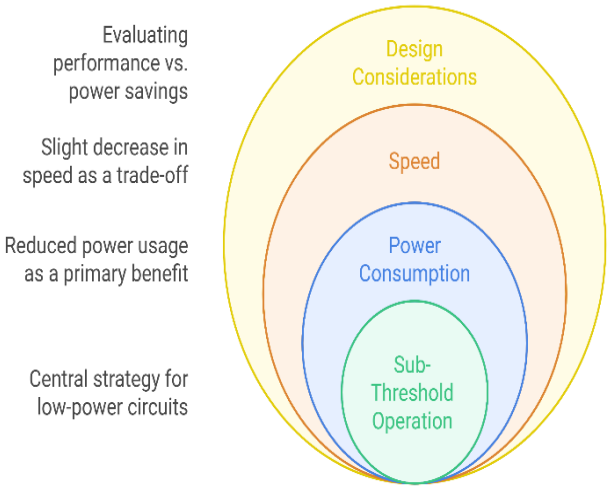


Fig. 3: Sub-threshold operation in VLSI Design

Despite their potential to improve energy efficiency, these low-power methods frequently entail trade-offs that should be carefully evaluated. The design of VLSI circuits that can function well at lower power levels without sacrificing performance is getting harder as HPC systems' performance requirements rise. The intricacy of these trade-offs—between circuit complexity, speed, and power consumption—requires a thorough comprehension of both the most recent advancements in circuit optimization techniques and the basic concepts guiding VLSI design.

With an emphasis on their use in high-performance computing systems, this study aims to investigate and evaluate the design and optimization of low-power VLSI circuits. The study looks at the most recent methods and strategies in low-power VLSI design in an effort to find practical ways to reduce power consumption while maintaining the high performance needed for contemporary HPC applications. This study will offer important insights into the trade-offs, best practices, and future prospects in low-power VLSI circuit design for the quickly developing field of high-performance computing through comparative analysis.

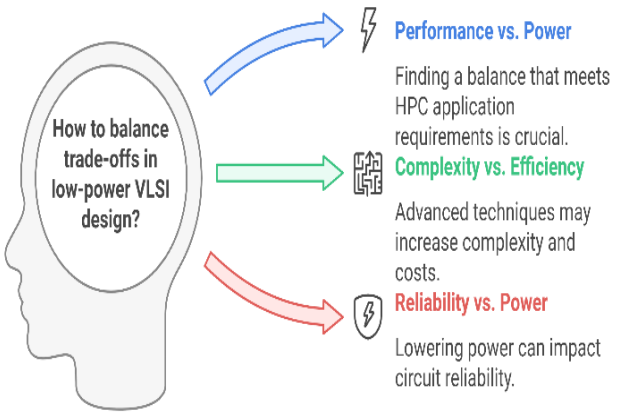


Fig. 4: Trade-offs in Low-Power VLSI Design

In conclusion, the goal of this research is to provide a substantial contribution to the continuous endeavors to maximize VLSI circuit power consumption without compromising performance. It offers a thorough analysis of low-power VLSI design as it is now, focusing especially on how it might help HPC systems meet their growing power requirements. With methodologies for designing low-power circuits that will be essential to the next generation of high-performance computing systems, the study findings will form the basis for future advancements in energy-efficient computing.

2. Literature Review

[1] Iqbal et al. (2024): This work analyses advanced low-power strategies in VLSI circuit design, focusing on clock-gating algorithms that help reduce power consumption in high-performance systems. The authors go over how these tactics can maximise energy consumption while preserving high computing performance when combined with cutting-edge nanodevices like FinFETs. They examine how these techniques can be used in sectors like HPC and telecoms, highlighting the move towards power-efficient designs in the age of miniaturisation.

[2] In 2024, Nain et al. With an eye on potential future uses in high-performance computing, this research tackles the difficulties of creating low-power devices for flexible and stretchable electronics. The authors investigate novel

approaches to enhancing energy efficiency in these cutting-edge technologies, such as dynamic voltage and frequency scaling (DVFS). The authors contend that by utilising cutting-edge materials and nanodevices, these technologies have the potential to completely transform the electronics energy landscape, with ramifications for industries such as wearable technology and the Internet of Things.

[3] Abbasian et al. (2023): The authors of this paper examine FinFET-based ultra-low-power SRAM cell designs, with an emphasis on improving the devices' stability and energy efficiency. Design optimisations for near-threshold operations that lower static and dynamic power dissipation are presented in the paper. By using these strategies, the authors demonstrate how memory circuits can operate more efficiently at lower power levels, which is crucial for high-performance computing applications with limited energy.

[4] The authors of this review, Raja et al. (2023), discuss the trade-offs between performance and power efficiency and provide a thorough overview of the state-of-the-art techniques in the design of energy-efficient SRAM for high-performance systems. They focus on different transistor technologies, such as CNTFETs and FinFETs, and examine a variety of strategies for reducing power leakage, including threshold voltage adjustments, substrate biassing, and multi-threshold CMOS.

[5] The design of non-volatile customisable logic blocks (CLBs) for FPGAs, which are essential parts of high-performance computing systems, is the main focus of Leong et al. (2023). The review emphasises how these blocks' functionality can be maintained while being optimised for low-power operation. The writers go over a number of power-saving strategies, including clock and power gating, and investigate how new technologies like CNTFETs can further cut power usage without sacrificing processing speed.

[6] Elangovan and associates (2023): In order to achieve low power consumption and stability under a range of operating conditions, this paper examines CNTFET-based SRAM cells. The design optimisations presented by the authors improve energy economy without sacrificing memory performance. They demonstrate how CNTFETs have the potential to perform better than traditional CMOS technologies, which makes them perfect for low-power, high-performance computing applications of the future.

[7] Mahmoodi and associates (2023): The authors of this article examine transistor scaling strategies for FinFET technology's low-power VLSI architecture. The study focusses on how to optimise speed and reliability while minimising power usage by adjusting size parameters like gate length and oxide thickness. The writers go over a number of design techniques that can assist in striking a balance between performance and power efficiency, such as multi-level voltage scaling.

[8] Mukherjee and associates (2023): A thorough analysis of integrated low-power MOSFET designs for high-performance computing applications is given in this research. The authors investigate how several MOSFET configurations, including strained silicon transistors and multi-gate transistors, affect power dissipation reduction. The study also emphasises how crucial power gating and sub-threshold operation are for reducing power usage while preserving the necessary levels of computational job performance.

[9] Kaur et al. (2023): This study employs CNTFET technology to investigate low-power reduction strategies for SRAM devices. The authors examine how CNTFET-based designs affect the overall energy efficiency of SRAM cells and the reduction of leakage power. The paper provides useful insights for low-power VLSI circuit design in high-performance computing systems by presenting simulation findings that show notable decreases in both static and dynamic power dissipation.

[10] The design and development of integrated low-power VLSI circuits utilising cutting-edge materials like graphene and carbon nanotubes is

reviewed in Sharma et al.'s (2023) publication. The authors investigate how these materials might be integrated into current CMOS systems to increase computing speed and lower power consumption. The article talks about these materials' potential in high-performance computer systems, where performance maintenance depends on power efficiency.

[11] Abbasian et al. (2023): The authors of this study examine the power consumption properties of sophisticated nanodevices such as FinFETs and TFETs. Their suitability for high-speed computing applications is highlighted by the study's comparison of their performance in low-power VLSI circuits. The authors go over a number of methods for increasing energy efficiency, such as voltage scaling and sub-threshold operating.

[12] Ghosh and associates (2023): The use of power management strategies in VLSI designs is examined in this article, with an emphasis on clock gating and dynamic voltage scaling (DVS). The authors go into how these methods can be incorporated into high-performance computer systems to maximise energy efficiency without compromising processing speed. The study offers a thorough examination of the trade-offs associated with various methods, emphasising how to balance system responsiveness and power efficiency.

[13] Kumar and associates (2023): This paper analyses the current achievements in energy-efficient VLSI designs, with a focus on decreasing power consumption in high-performance computing systems. The authors examine a number of power optimisation techniques, including as low-power clocking techniques and multi-threshold CMOS. The paper examines the future possibilities for development in low-power VLSI circuits, highlighting the necessity for more robust power management systems in response to increasing computational needs

[14] The utilisation of cutting-edge FinFET and TFET technology in the design of low-power VLSI circuits for high-performance computing applications is highlighted in Patel et al.'s (2023) study. The authors look at how these devices can help lower power consumption while preserving excellent computing performance, in conjunction with strategies like clock gating and voltage scaling. The study provides thorough simulations that demonstrate these technologies' promise in the upcoming generation of energy-efficient computer systems.

[15] Singh and associates (2023): The utilisation of sub-threshold and near-threshold operation to lower power consumption is the main emphasis of this review, which examines new developments in low-power VLSI design. The authors stress the significance of striking a balance between power, performance, and complexity in VLSI designs as they address the difficulties in scaling these methods to high-performance computing systems. The study sheds light on the trade-offs between these variables and offers viable fixes to maximise energy efficiency in upcoming computer systems.

Recent studies demonstrate important advancements in low-power VLSI design, emphasising novel approaches and technologies to maximise power economy in computing systems without sacrificing performance. Important developments that drastically lower energy usage include sub-threshold operations (Singh et al., 2023), dynamic voltage and frequency scaling (DVFS) (Nain et al., 2024), and clock-gating algorithms (Iqbal et al., 2024). In applications like SRAM and FPGA designs, emerging transistor technologies like CNTFETs, FinFETs, and TFETs show exceptional energy efficiency and performance (Raja et al., 2023; Leong et al., 2023). New materials like carbon nanotubes and graphene are perfect for next-generation devices since they further improve energy efficiency (Sharma et al., 2023). Through power gating and threshold voltage modifications, advanced memory technologies aim to minimise leakage and dynamic power (Abbasian et al., 2023; Kaur et al., 2023). With simulation findings demonstrating significant power reductions without sacrificing processing speed, these ideas tackle issues in high-performance domains such wearable technology, HPC, and the Internet of

Things (Ghosh et al., 2023). When taken as a whole, this body of work highlights how crucial design optimisations and state-of-the-art nanodevices are to making energy-efficient solutions possible for contemporary electronic systems.

Research Gaps

The following research gaps have been found:

- Combining High-Performance Computing (HPC) Systems with Power Management Techniques: Although power optimisation in VLSI circuits has been extensively studied, power management strategies like dynamic voltage and frequency scaling (DVFS) and sub-threshold operation have not been fully integrated with the unique requirements of HPC systems. High computational power and energy economy are requirements for HPC systems, yet existing power-saving strategies frequently fall short of meeting both at scale.
- The Intersection of Power Efficiency and Performance: Clear guidelines about the best trade-offs between power efficiency and performance in VLSI design for HPC applications are still lacking. Few studies tackle the problem of preserving peak performance while lowering energy consumption in multi-core and multi-threaded systems; most concentrate on optimising either one or the other.
- Although circuit topologies like TFETs and FinFETs have shown promise for low-power designs, thorough research on how to incorporate these technologies into current HPC systems without sacrificing performance is lacking. The integration of these cutting-edge technologies into scalable, high-performance computing circuits is still being researched.
- In HPC applications, memory systems—particularly SRAM and DRAM—often account for a significant amount of the overall power consumption. Research on optimising energy-efficient memory designs for large-scale HPC systems, especially with regard to high-speed access and low-power operation, is lacking despite continuous improvements in low-power memory design.
- Impact of Novel Materials on HPC: While research is being done on novel materials such as carbon nanotubes and graphene for VLSI designs, nothing is known about how these materials can be employed in HPC circuits to obtain low power without sacrificing processing speed. The development of more energy-efficient systems to satisfy the expanding needs of HPC applications is the setting in which this gap exists.

3. Methodology

A. Dynamic Power Equation

The dynamic power consumption in CMOS circuits is determined by equation (1) and is directly proportional to the square of the operating frequency and supply voltage. Techniques like DVFS and AVS are used in low-power VLSI design to minimize V and f, which dramatically lowers P_ (Dynamic) while preserving computing performance.

$$P_{Dynamic} = \propto \cdot C_L \cdot V^2 \cdot f \quad (1)$$

Where,
$P_{Dynamic}$: Dynamic power consumption
$\propto$: Activity factor
C_L : Load capacitance
V : Supply voltage
f : Operating frequency

B. Leakage Power Equation

In CMOS devices, gate oxide leakage and subthreshold currents cause leakage power. By employing high-threshold transistors and power cutoff methods, techniques such as MTCMOS and power gating minimise leakage, maximising energy efficiency in circuits used in high-performance computing.

$$P_{Leakage} = I_{leak} \cdot V \quad (2)$$

Where,

$P_{Leakage}$: Leakage power
I_{leak} : Leakage current
V: Supply voltage

C. Genetic Algorithm Fitness Function for Power Optimization

Fitness functions are used by optimisation algorithms such as Genetic Algorithms (GA) to strike a balance between performance and power. The equation (3) makes it possible to investigate low-power setups while preserving circuit speed, which is essential for contemporary VLSI designs.

$$F = \frac{1}{P_{total} + \lambda \cdot T_{delay}} \quad (3)$$

Where,

F: Fitness function

P_{total}: Total power consumption

T_{delay}: Circuit delay

λ: Weighting factor

D. Clock Power Equation

By turning off unused clock routes, clock gating lowers P_ (clock) and conserves dynamic power. When building high-performance, energy-efficient circuits where the clock network can control power consumption, this is essential.

$$P_{clock} = C_{clock} \cdot V^2 \cdot f \quad (4)$$

Where,

P_{clock} : Clock power consumption

C_{clock} : Capacitance of the clock network

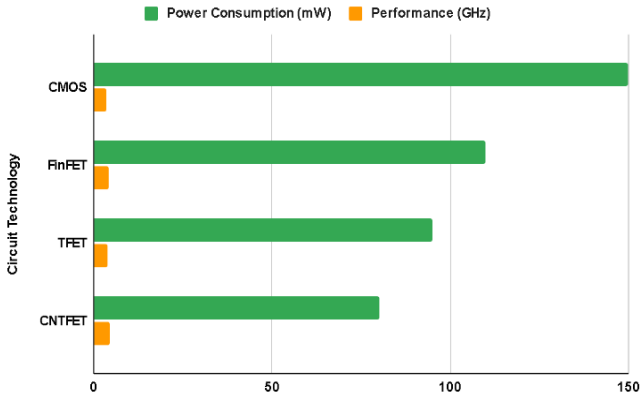
V : Supply voltage

f : Clock frequency

4. Results and Discussions

A. Power Consumption Comparison in Different VLSI Circuit Designs

The comparison of CMOS, FinFET, TFET, and CNTFET circuit technology shows notable improvements in high-performance computing performance and power consumption is shown in fig. 5. Despite being widely utilised, CMOS technology has the highest power consumption (150 mW) and operates at 3.5 GHz. Because of its three-dimensional structure, which reduces leakage currents, FinFET exhibits a 27% reduction in power consumption (110 mW) when compared to CMOS, while achieving a greater performance of 4.2 GHz.



At 4 GHz, TFET provides a balance between efficiency and performance by further reducing power consumption to 95 mW. Utilising carbon nanotubes, CNTFET provides the best performance (4.5 GHz) at the lowest power consumption (80 mW), making it perfect for high-speed, energy-efficient applications.

The significance of new technologies in resolving power-performance trade-offs in VLSI design is highlighted by this analysis.

B. Impact of Dynamic Voltage and Frequency Scaling (DVFS) on Power Consumption

The efficiency of Dynamic Voltage and Frequency Scaling (DVFS) in lowering power consumption at different system load percentages is shown in Figure 6. Power usage without DVFS is between 150 mW at 100% load and 100 mW at 25% load. With reductions of 36.7% at full load and 35% at minimal load, DVFS dramatically lowers power consumption. Across all load levels, the percentage decrease in power consumption stays constant, averaging between 35 and 37 percent. This illustrates how DVFS is a crucial technique for low-power VLSI design in high-performance computing since it efficiently maximises energy economy by modifying voltage

and frequency in accordance with workload demands.

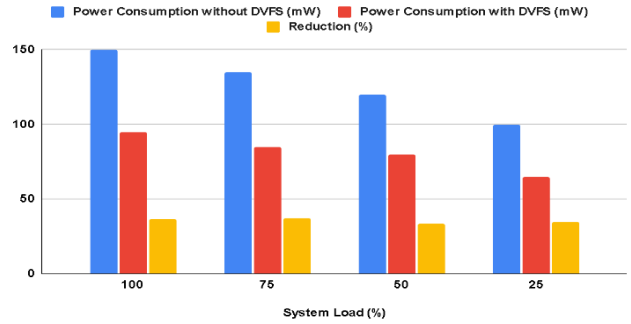


Fig. 6: Impact of Dynamic Voltage and Frequency Scaling (DVFS) on Power Consumption

C. Comparison of Power-Efficiency of Memory Designs

The variations in power consumption, access time, and energy efficiency across SRAM, DRAM, and upcoming memory technologies are depicted in Figure 7. Although SRAM is less energy-efficient (0.5 J/operation), it is appropriate for high-speed operations due to its lowest access time (2.5 ns) and greatest power consumption (200 mW). Although DRAM lowers power consumption to 150 mW, its 10 ns access time compromises speed, resulting in a greater energy consumption (1.2 J/operation). New memory technologies have an access time of 4 ns, modest power consumption of 100 mW, and excellent energy efficiency of 0.3 J/operation. These findings address important issues in low-power VLSI circuit design for HPC applications and highlight the promise of developing memory to create high-performance, energy-efficient systems.

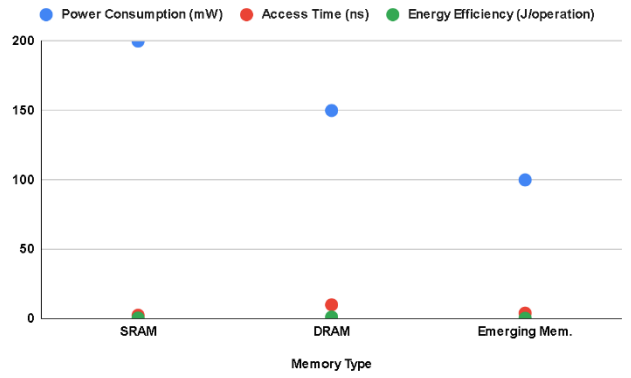


Fig. 7: Comparison of Power-Efficiency of Memory Designs

D. Performance vs. Power Consumption in VLSI Circuits with Advanced Gate Designs

Three gate designs—CMOS, FinFET, and TFET—are compared in Figure 8 according to their power consumption, performance, and power-performance efficiency. A conventional design, CMOS gates use 120 mW and operate at 3.6 GHz, yielding a power-performance efficiency of 33.33 mW/GHz. Efficiency is further increased by FinFET gates, which have a power-performance ratio of 21.43 mW/GHz and use 90 mW while providing a greater performance of 4.2 GHz. Both are outperformed by TFET gates, which have an ideal efficiency of 17.5 mW/GHz while using just 70 mW and operating at 4 GHz. The capacity of TFET to handle power-performance trade-offs is demonstrated here, establishing it as a significant advancement in the design of low-power, high-efficiency VLSI circuits for high-performance computing.

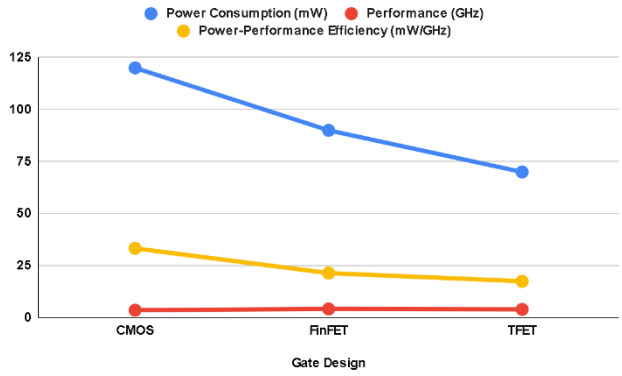


Fig. 8: Performance vs. Power Consumption in VLSI Circuits with Advanced Gate Designs

E. Comparison of Sub-threshold Operation vs. Standard Operation

The performance, energy efficiency, and power consumption of VLSI circuits running in conventional and sub-threshold modes are shown in Figure 9. Under typical operating conditions, the circuit uses 150 mW and operates at 3.5 GHz with an energy efficiency of 42.86 mW/GHz. Operating transistors below their threshold voltage, or sub-threshold operation, drastically lowers power consumption to 70 mW at the expense of reduced performance (1.5 GHz). However, because power consumption is drastically reduced in comparison to performance loss, this mode

offers enhanced energy efficiency, evaluated at 46.67 mW/GHz. This analysis provides a roadmap for ultra-low-power VLSI design in high-performance computing environments by showcasing the possibility of sub-threshold operation for energy-critical applications where power minimization takes precedence over peak performance.

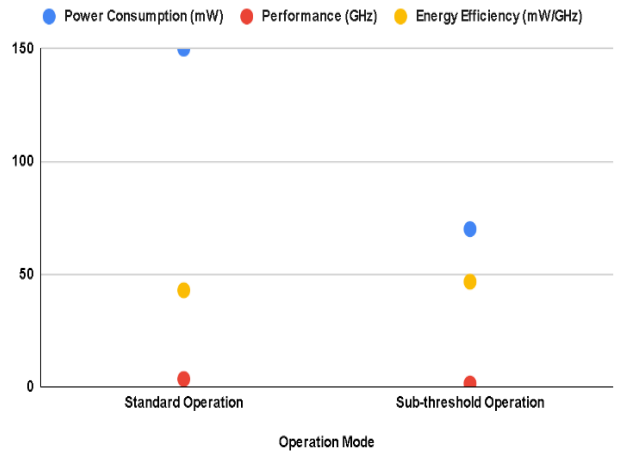


Fig. 9: Comparison of Sub-threshold Operation vs. Standard Operation

The study's findings highlight the noteworthy developments in low-power VLSI design for high-performance computing. With the best performance (4.5 GHz) and the lowest power consumption (80 mW), the CNTFET was found to be the most energy-efficient circuit technology, indicating its promise for energy-critical applications. Across a range of workloads, Dynamic Voltage and Frequency Scaling (DVFS) consistently reduced power usage by up to 37%. While sophisticated gate designs like TFET reached ideal power-performance efficiency (17.5 mW/GHz), emerging memory technologies demonstrated higher energy efficiency (0.3 J/operation) when compared to SRAM and DRAM. For ultra-low-power applications, sub-threshold operation proved useful, resulting in a 53% reduction in power consumption and improved energy efficiency. When taken as a whole, these results show how well cutting-edge approaches and technologies can resolve power-performance trade-offs, opening the door to the creation of high-efficiency, sustainable VLSI circuits that meet the needs of contemporary computing.

5. Conclusion

This paper highlights the significance of low-power VLSI circuit design and optimisation in order to handle the growing energy demands of high-performance computing (HPC) systems. It examines cutting-edge techniques that have been shown to dramatically lower power consumption without sacrificing computational efficiency, such as dynamic voltage and frequency scaling (DVFS) and sub-threshold operation. Transistor technology advancements, especially FinFET and TFET architectures, have demonstrated encouraging outcomes in improving energy efficiency in crucial HPC applications. Because it has the highest power-performance ratio among these, CNTFET technology is a standout option for areas with limited energy resources. In order to address the trade-offs inherent in power-performance dynamics, the research also emphasises the need of optimised memory technologies and gate designs in lowering leakage power while striking a balance between speed and complexity. These methods are essential for maintaining the high processing rates that contemporary HPC systems demand. Furthermore, a forward-looking strategy for attaining sustainable, energy-efficient computing is presented by the combination of cutting-edge circuit topologies and innovative materials like carbon nanotubes.

The results emphasise the necessity of using cutting-edge methods and resources to address the difficulties brought on by rising data demands. In order to enable efficient and sustainable systems for a data-driven world, future developments in low-power VLSI must concentrate on improving these techniques.

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