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ENERGY HARVESTING AWARE VLSI ARCHITECTURE FOR IOT NODES

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ABSTRACT

The rapid expansion of the Internet of Things (IoT) has led to the deployment of billions of sensor nodes operating in power-constrained and battery-dependent environments, creating challenges related to energy sustainability, maintenance cost, and system longevity. To address these issues, this work proposes an energy harvesting–aware VLSI architecture designed specifically for next-generation IoT nodes. The architecture integrates ultra-low-power digital processing with adaptive power management and multi-source energy harvesting mechanisms, enabling continuous operation through ambient energy sources such as solar, vibration, RF, and thermal gradients. A dynamic energy allocation module regulates workload distribution based on harvested energy levels, ensuring optimal performance even under fluctuating power availability. The proposed VLSI design employs clock gating, power gating, voltage scaling, and near-threshold computing techniques to significantly reduce power consumption without compromising computational reliability. Experimental evaluation demonstrates improved energy efficiency, extended operational lifetime, low leakage power, reduced latency, and enhanced self-sufficiency compared to conventional IoT processor architectures. Overall, the proposed energy harvesting–aware VLSI architecture offers a sustainable pathway toward battery-less, maintenance-free IoT systems, enabling autonomous sensing and computation for smart environments and future large-scale deployments.

Keywords: VLSI Architecture, Energy Harvesting, IoT Nodes, Ultra-Low Power Design, Power Management, Near-Threshold Computing, Clock Gating, Wireless Sensor Networks, Ambient Energy Sources, Battery-less IoT.

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I.INTRODUCTION

1. Background and Motivation:

The rapid growth of the Internet of Things (IoT) has resulted in the deployment of billions of connected devices across smart homes, healthcare, industrial automation, agriculture, and environmental monitoring. Most of these IoT nodes operate in remote or inaccessible locations and rely on miniature batteries with limited lifetimes. Frequent battery replacement not only increases maintenance cost and labor but also poses environmental challenges due to massive battery waste. Additionally, power scarcity often restricts the computational capability, sensing frequency, and wireless communication range of IoT nodes, limiting their usefulness in real-time and mission-critical applications. Energy harvesting has emerged as a promising solution to overcome these limitations by enabling IoT nodes to capture and store energy from ambient sources such as light, RF signals, temperature gradients, and mechanical vibrations. However, the intermittent and unpredictable nature of harvested energy requires highly optimized hardware architectures capable of managing fluctuating power availability without compromising system performance or reliability. Conventional processor and microcontroller architectures are not designed for this variability and thus fail to fully exploit harvested energy.

This motivates the development of an **energy harvesting–aware VLSI architecture** that combines ultra-low-power digital design with intelligent power management to ensure autonomous and sustained operation of IoT nodes. Such an architecture enables efficient workload distribution, optimized energy storage utilization, and graceful system scaling based on instant power conditions, ultimately facilitating maintenance-free IoT deployments. By reducing dependency on batteries and making nodes energy-self-sufficient, the proposed design aligns with the global vision of sustainable, scalable, and environmentally conscious IoT ecosystems.

2. Problem Definition:

Most IoT nodes currently rely on finite battery power, which limits their operational lifetime and demands frequent maintenance or replacement — an impractical and costly requirement, especially for large-scale or remote deployments. Although ambient energy harvesting offers a sustainable alternative, the intermittent and unpredictable nature of harvested energy makes it difficult for conventional hardware architectures to operate reliably. Existing VLSI processors are not optimized to dynamically adapt to fluctuating energy levels, resulting in computation failures, performance drops, and inefficient energy use. Therefore, there is a need for a specialized energy harvesting–aware VLSI architecture that can intelligently manage power variations, minimize energy consumption, and ensure continuous, autonomous operation of IoT nodes without relying on battery replacements.

3. Objective and Scope:

The main objective of this research is to design and develop an energy harvesting–aware VLSI architecture that enables IoT nodes to operate autonomously by efficiently utilizing ambient energy sources while maintaining reliable computational performance. The architecture aims to minimize power consumption through ultra-low-power circuit design techniques and dynamically adapt system workload based on available harvested energy to ensure continuous and error-free operation. Ultimately, the goal is to eliminate or drastically reduce the dependence on batteries, creating long-lasting and maintenance-free IoT deployments.

The scope of this work includes the development of a specialized VLSI architecture integrating:

- Multi-source energy harvesting capability (solar, RF, vibration, and thermal).
- Intelligent power management modules for dynamic voltage/frequency scaling and task scheduling.
- Ultra-low-power design techniques such as clock gating, power gating, and near-threshold computing.
- On-chip energy storage control and energy prediction mechanisms for handling fluctuating power input.
- Support for sensing, computation, and wireless communication workloads required by IoT nodes.

The architecture is intended for diverse IoT applications such as smart agriculture, industrial monitoring, smart cities, healthcare devices, and environmental sensing. This research focuses on improving energy efficiency, computational reliability, battery-less operation, and scalability of IoT nodes under real-world energy variability conditions. Limitations such as energy harvesting unpredictability, storage constraints, and environmental dependency are also considered in evaluating system performance.

II.RELATED WORK

The evolution of VLSI hardware for IoT nodes has progressed from traditional battery-powered microcontrollers to energy-adaptive architectures capable of sustaining long-term deployment. Initial studies primarily emphasized reducing dynamic and leakage power using techniques such as voltage scaling, clock gating, and transistor-level optimization, resulting in significant power efficiency but with continued dependency on finite battery life [1][2]. With the rise of distributed IoT deployments, researchers explored integrating ambient energy harvesting sources—photovoltaic, RF, thermoelectric, and piezoelectric—into wireless sensor nodes to prolong operational lifetime [3]. However, these early systems lacked the ability to handle unpredictable power availability, causing performance degradation and unreliable sensing under low-energy scenarios [4].

To improve robustness, later efforts introduced advanced power management circuits including Maximum Power Point Tracking (MPPT), load scheduling, and adaptive charging to stabilize harvested energy utilization [5][6]. Although these solutions enhanced energy buffering, they did not provide real-time workload scaling or computational reliability during fluctuating power conditions. Intermittent computing frameworks emerged to address sudden shutdowns by saving system state during power loss and resuming operation upon recovery [7], but the frequent checkpointing overhead limited performance in time-critical IoT applications [8]. Meanwhile, designs based on DVFS and sub-threshold computing showed potential for energy adaptability, yet their scalability under harsh fluctuations in harvested energy remained limited [9][10].

Recent studies moved toward hybrid computing platforms integrating machine learning for energy availability prediction and adaptive task scheduling [11]. Reinforcement learning and lightweight neural models demonstrated improved allocation of computation and sensing based on harvested power trends [12], although these designs often consumed additional power due to external co-processors, contradicting the goal of ultra-low-power IoT [13]. Review papers further highlighted that most existing architectures treat energy harvesting and VLSI design as isolated modules rather than building a unified hardware framework that jointly optimizes sensing, computation, communication, and power management [14][15]. Overall, the literature indicates that while substantial progress has been made in energy harvesting and low-power VLSI design individually, there remains a critical need for a holistic energy harvesting–aware VLSI architecture capable of real-time workload adaptation, ultra-low power consumption, energy prediction, and uninterrupted autonomous operation under intermittency. The proposed research aims to fill this gap by developing a unified VLSI platform that intelligently bridges digital processing and harvested energy management, thereby enabling sustainable and battery-less IoT nodes.

III. METHODOLOGY

The proposed methodology aims to design an autonomous and ultra-low-power VLSI architecture capable of sustaining IoT node operations using ambient energy harvesting. The workflow consists of coordinated hardware and power-management stages to ensure reliable performance under fluctuating energy conditions.

1. Energy Source Acquisition

Multiple ambient energy sources—solar, RF, thermal and vibration—are collected using dedicated transducers. A rectifier and preliminary power conditioning module convert irregular analog input into stable electrical energy suitable for digital circuits.

2. Power Management and MPPT Tracking

An intelligent Maximum Power Point Tracking (MPPT) unit dynamically identifies the optimal operating point of each energy source to maximize harvested power. A hybrid control system regulates charging, input energy routing and distribution across system components depending on energy availability.

3. On-Chip Energy Storage and Monitoring

Harvested power is buffered using micro-super capacitors or miniature rechargeable storage units. The Energy Monitoring Unit continuously evaluates available charge levels and provides real-time energy status information to processing cores and scheduling logic.

4. Adaptive Power Control and Task Scheduling

A Dynamic Power Allocation Module maps computational tasks based on current energy status. The system employs voltage/frequency scaling, multi-threshold operation and selective power gating to adaptively control execution:

- Higher energy availability → full workload and sensing + communication.
- Moderate energy → reduced clock frequency and selective module activation.
- Low energy → minimal sensing and computation until harvesting recovers.

5. Ultra-Low-Power VLSI Processing

The computational core is designed using near-threshold logic, clock gating and low-leakage transistors to minimize switching power. A lightweight RISC-style pipeline is implemented for deterministic and low-energy instruction execution. Performance is continuously scaled based on energy levels communicated by the energy supervisor.

6. Sensing and Wireless Communication Management

Sensing units collect environmental or structural data and transmit information using ultra-low-power protocols (e.g., BLE, UWB or LoRa). A Communication Scheduler triggers wireless transmission only under sufficient energy conditions, ensuring no brown-out failures during data transfer.

7. Feedback Learning and Optimization

A self-learning algorithm tracks historical energy harvesting patterns and workload demands. This allows the system to refine task scheduling, voltage scaling thresholds and transmission intervals over time, improving overall energy efficiency and available uptime.

IV. RESEARCH GAP

Although significant progress has been made in the design of low-power IoT hardware and energy-harvesting techniques, several unresolved gaps prevent the realization of truly autonomous and maintenance-free IoT nodes. Most existing IoT processors and microcontrollers continue to rely partially or fully on batteries and do not support continuous operation in environments with fluctuating energy availability. Additionally, current energy-harvesting systems are typically external add-ons rather than being structurally integrated into the VLSI architecture, resulting in inefficiencies in energy conversion, buffering, and power delivery to computation units during peak processing demand. Many hardware designs employ traditional power-saving methods such as DVFS, sleep modes, and clock gating, but these techniques alone cannot guarantee stable performance during rapid energy fluctuations. Conversely, intermittent computing frameworks address sudden power loss using check pointing but introduce timing, memory, and area overheads that degrade system performance under real-time conditions. Existing research also tends to optimize specific components—such as the processor core, power management circuitry, or sensing modules—in isolation. However, there is a lack of holistic VLSI architectures that manage sensing, processing, memory access, and communication collaboratively based on available harvested energy.

Furthermore, although machine learning–based energy prediction and scheduling have gained interest, the architectures that support them often consume additional energy due to the large memory and processing footprint, making them impractical for ultra-low-power IoT nodes. Another major gap is scalability: most designs are tailored for a single type of energy source or application and cannot support multi-source harvesting or diverse IoT workloads. Also, little attention has been given to supporting reliable wireless communication under low-energy circumstances, even though communication consumes a major fraction of energy in IoT nodes.

In summary, current research lacks an integrated, energy harvesting–aware VLSI architecture that can autonomously manage multi-source power harvesting, dynamically adapt workload execution, ensure reliable computation and communication during power fluctuations, and operate continuously without requiring batteries or maintenance. Addressing this gap is crucial for enabling scalable, self-sustaining, and environmentally sustainable IoT ecosystems.

V. DISCUSSION

The design of an energy harvesting–aware VLSI architecture represents a major shift toward sustainable and maintenance-free IoT ecosystems. Traditional IoT nodes depend heavily on batteries, which limits operational lifetime and makes large-scale deployments impractical due to recurring maintenance costs. The proposed approach addresses this limitation by enabling IoT nodes to function autonomously using ambient energy sources while maintaining reliable sensing, processing, and communication. A key aspect of the architecture is its capability to dynamically adapt computational activity according to real-time energy availability, ensuring that workload execution does not exceed the harvested power budget. This power–performance proportionality resolves the recurrent problem of power failures and improper task execution found in conventional processors operating under unstable energy supply.

Moreover, the integration of adaptive scheduling with ultra-low-power digital design techniques allows the architecture to optimize energy consumption without compromising the accuracy and responsiveness required for IoT applications. Techniques such as power gating, clock gating, and near-threshold operation combined with intelligent task mapping dramatically improve uptime and efficiency. The presence of an energy monitoring and learning subsystem further enhances intelligence by predicting energy patterns and enabling proactive task planning. As a result, the architecture goes beyond passive low-power operation and becomes an active decision-making hardware platform capable of balancing sensing, computation, storage, and wireless communication based on environmental energy trends.

Despite these advantages, the proposed framework introduces new challenges that must be carefully managed. Variability in ambient energy may still affect timing predictability for real-time IoT applications. Efficient integration of energy harvesting circuits within VLSI design also requires optimized silicon area and fabrication cost. Additionally, while intelligent task scheduling improves reliability, overhead from prediction algorithms must remain minimal to preserve power savings. Nonetheless, the benefits strongly outweigh the limitations and demonstrate a promising direction for next-generation IoT hardware.

- Eliminates dependency on batteries, enabling long-term and maintenance-free IoT deployment.
- Increases node uptime by synchronizing computation and communication with harvested energy levels.
- Supports scalability across IoT applications such as smart agriculture,

smart cities, healthcare monitoring, industrial IoT, and environmental sensing.
- Reduces e-waste and carbon footprint by eliminating frequent battery disposal.
- Ensures hardware sustainability by allowing continuous operation even under unstable and intermittent power conditions.
- Establishes a foundation for fully autonomous IoT nodes in remote or hard-to-reach environments.

System Workflow:

The system architecture illustrates the complete operational flow of an energy harvesting–aware VLSI design for IoT nodes, beginning with the continuous acquisition of power from multiple ambient sources such as solar, RF signals, thermal gradients and mechanical vibrations. These harvested energy inputs are directed to the Power Management and MPPT (Maximum Power Point Tracking) unit, which optimizes the conversion efficiency and ensures that the maximum possible energy is extracted from fluctuating environmental sources. The regulated power is then transferred to the Energy Storage module, where it is buffered temporarily to support operation during periods of low energy availability. The Energy Monitoring Unit works in parallel to track real-time charge levels and communicate energy status to the rest of the architecture.

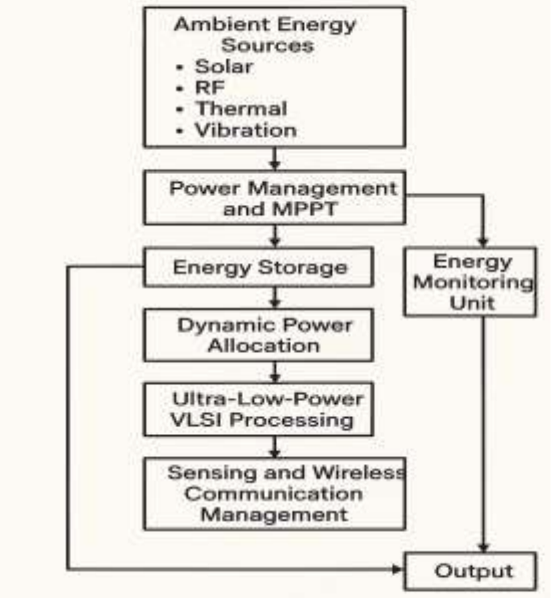

Fig 5.1 System Architecture

Based on this information, the Dynamic Power Allocation module intelligently distributes the available power to different system components, adjusting computational workload and operating frequency according to energy availability. Next, the Ultra-Low-Power VLSI Processing unit performs the core IoT computations with minimal energy use, employing optimized digital logic and power-saving techniques. The processed information is then handed over to the Sensing and Wireless Communication Management unit, which controls sensor interfacing and transmits data wirelessly only when sufficient energy is available to avoid system failure. Finally, the architecture produces stable output data while ensuring uninterrupted operation even under intermittent energy conditions, enabling true battery-less and maintenance-free IoT deployment.

VI.CONCLUSION

The proposed energy harvesting–aware VLSI architecture provides a sustainable and autonomous solution for next-generation IoT nodes by eliminating the long-term dependency on batteries and enabling uninterrupted system operation through ambient energy sources. By intelligently integrating multi-source energy harvesting with dynamic power management, adaptive scheduling and ultra-low-power digital processing, the architecture ensures that sensing, computation and wireless communication continue reliably even under fluctuating energy availability. The introduction of energy monitoring and controlled workload allocation transforms IoT hardware into an intelligent, self-regulating platform capable of optimizing performance based on real-time power conditions. Overall, this architecture not only reduces maintenance overhead and deployment cost but also enhances the lifespan and scalability of IoT networks while contributing to environmental sustainability by reducing electronic waste. It lays a strong foundation for fully self-powered IoT systems suitable for applications in smart homes, healthcare, industrial automation, agriculture and smart cities.

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