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Energy-efficient circuit design strategies for IoT devices: A comprehensive review

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Abstract

The rapid expansion of the Internet of Things (IoT) has created a growing demand for devices that operate efficiently under stringent power and energy constraints. To enable long-term functionality, especially in battery-powered and energy-harvesting IoT systems, energy-efficient circuit design has become a critical research area. This review presents a comprehensive analysis of the latest advancements in energy-efficient circuit design techniques for IoT devices. It explores various low-power strategies, including energy harvesting technologies, dynamic voltage and frequency scaling (DVFS), sub-threshold logic, and sleep mode techniques. Additionally, the study examines the role of ultra-low-power processors, communication modules, and sensors in enhancing the overall energy efficiency of IoT systems. Key challenges such as sustaining performance within limited energy budgets, reducing leakage power, and balancing power, performance, and area trade-offs are also addressed. Furthermore, the review highlights emerging trends and future research directions focused on minimizing energy consumption while ensuring scalable and reliable IoT deployments.

Keywords: Sensors; Clock Gating; Energy Harvesting; Internet of Things (IoT); Dynamic Voltage and Frequency Scaling (DVFS)

1. Introduction

The Internet of Things (IoT) is revolutionizing the way we interact with our environment by enabling seamless connectivity between physical objects and the digital world. From smart homes and industrial automation to healthcare monitoring and environmental sensing, IoT devices have become an integral part of modern life. However, the exponential growth of IoT devices has led to a critical challenge—managing energy consumption. Since most IoT devices rely on limited power sources such as batteries or energy-harvesting systems, achieving highly energy-efficient designs is essential for ensuring long-term, autonomous operation.

Energy-efficient circuit design has emerged as a crucial solution to extend battery life and minimize the environmental impact of the vast number of IoT devices being deployed worldwide. Traditional circuit design approaches, which prioritize performance, are often unsuitable for IoT applications that require ultra-low power consumption. As a result, researchers and engineers are focusing on innovative design techniques and advanced technologies to overcome energy constraints while maintaining functionality and reliability.

This study provides a comprehensive review of the most effective energy-efficient circuit design strategies for IoT devices. It explores key low-power techniques, including clock gating, dynamic voltage and frequency scaling (DVFS), sub-threshold operation, and sleep modes. Additionally, it examines the role of energy harvesting methods and ultra-low-power sensors in enhancing the energy efficiency of IoT networks. By synthesizing recent advancements in the field, this review aims to offer valuable insights for researchers and industry professionals, highlighting the key challenges, trade-offs, and opportunities in designing sustainable and energy-efficient IoT technologies.

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2. Power Consumption in IoT Devices

The energy consumption of IoT devices plays a critical role in determining their operational lifespan, particularly for systems powered by batteries or energy-harvesting technologies. These devices generally comprise three core components: sensors, communication modules, and processing units, each with distinct power demands. The overall energy profile of an IoT device is influenced by various factors, including the frequency of data transmission, the intensity of sensing operations, and the complexity of computational tasks. Optimizing power consumption across these components is essential to enhance efficiency, prolong device functionality, and support sustainable IoT deployments.

2.1. Sensors

Sensors in IoT devices play a vital role in monitoring environmental parameters such as temperature, pressure, motion, and humidity. While individual sensing operations typically consume minimal power, continuous operation can lead to significant energy consumption. To mitigate this, many IoT systems employ power-saving strategies such as duty cycling, where sensors are periodically turned off to conserve energy, or event-driven sensing, which activates sensors only in response to meaningful changes in the environment.

2.2. Communication Module

Wireless communication is among the most power-intensive tasks in IoT devices, with data transmission—particularly over long distances—consuming substantial energy. Various communication protocols, including Wi-Fi, Bluetooth Low Energy (BLE), Zigbee, and LoRa, offer different trade-offs in terms of range, data rate, and power efficiency. Low-power IoT networks often rely on optimized protocols like BLE and Zigbee, which are specifically designed to minimize energy consumption while ensuring reliable data transmission. Selecting the appropriate communication technology is crucial for balancing power efficiency and connectivity in IoT applications.

2.3. Processing Units

The microcontroller or processor serves as the central unit managing an IoT device's operations, including data processing, communication, and sensor control. Its power consumption is influenced by factors such as computational complexity, operating frequency, and the efficiency of power management techniques. To optimize energy usage, IoT devices often incorporate ultra-low-power microcontrollers designed for minimal power consumption during data processing. Additionally, techniques like dynamic voltage and frequency scaling (DVFS) help conserve energy by adjusting the processor's voltage and frequency in response to workload demands, ensuring efficient operation while extending battery life.

Table 1 Components & their Power consumption characteristics

Component	Description	Power Consumption Characteristics
Sensors	Responsible for collecting data from the environment.	Low power during active sensing, but continuous operation can drain power.
<i>Communication Modules</i>	Wireless data transmission modules such as Wi-Fi, BLE, Zigbee, and LoRa that enable data exchange between IoT devices and the network.	One of the most power-hungry components. Low-power communication protocols like BLE and Zigbee help minimize Energy consumption.
<i>Processing Units</i>	Microcontroller (MCU) or processor that controls operations and manages tasks like data processing and communication.	Power usage depends on computational load.
<i>Power Management (Modes)</i>	IoT devices switch between different operational modes, such as active, idle, and sleep, to optimize energy consumption.	Power-saving modes like sleep and idle drastically reduce power usage.
<i>Battery/Energy Harvesting</i>	The power source for IoT devices, typically batteries or energy-harvesting systems like solar or RF energy scavenging.	Battery life heavily depends on power consumption efficiency.

3. Low-Power Design Techniques for IoT

Designing energy-efficient circuits for IoT devices is essential to extend battery life and ensure long-term autonomous operation. Several low-power design techniques have been developed to address the power consumption challenges associated with IoT devices, especially those that rely on limited power sources or energy harvesting. Below are the key techniques used to minimize power usage.

3.1. Sub threshold Logic Design

Sub-threshold logic operates transistors below their threshold voltage, reducing dynamic and leakage power consumption significantly. Although this technique reduces the switching speed of the device, it is highly effective for ultra-low-power IoT devices that do not require high performance. This technique is ideal for applications where energy conservation takes precedence over processing speed.

3.2. Dynamic voltage and frequency scaling

DVFS allows the system to dynamically adjust the voltage and operating frequency based on real-time workload requirements. By lowering the voltage and frequency during periods of low computational demand, DVFS reduces the power consumption of the processing unit. This is particularly useful in IoT devices that experience varying workloads, such as sensors that only occasionally need to process large amounts of data.

3.3. Clock gating and power gating

Clock gating disables the clock signal to specific parts of a circuit when those parts are not in use, effectively reducing dynamic power consumption. Power gating, on the other hand, cuts off the power supply to unused sections of a circuit, significantly reducing leakage power. These techniques are widely used in IoT systems to conserve power during idle periods or when only certain functionalities are needed.

3.4. Multi -V_{th} and multi - VDD Design Techniques

Multi-V_{th} (threshold voltage) design allows different parts of a circuit to operate at varying threshold voltages, optimizing the trade-off between performance and power consumption. Similarly, Multi-V_{dd} (supply voltage) design uses different voltage levels within a system, applying higher voltages to performance-critical parts and lower voltages to less demanding components. This technique helps to strike a balance between power efficiency and system performance.

3.5. Duty cycling

Duty cycling is commonly used in wireless communication and sensing. It involves turning off or placing components into a low-power sleep mode when they are not in use and waking them up periodically for operation. This significantly reduces power consumption, especially in devices where continuous operation is unnecessary, such as environmental sensors that only need to measure and transmit data periodically.

3.6. Energy harvesting integrating

Incorporating energy harvesting into IoT devices allows them to supplement or replace batteries by scavenging energy from ambient sources like solar, vibration, or RF signals. While this doesn't directly reduce the device's power consumption, it offsets the energy needs, enabling the device to operate for longer periods without relying solely on a battery.

Table 2 Low-Power Design Techniques & their Power saving Mechanism

Technique	Description	Power Savings Mechanism	Applications in IoT
<i>Sub-Threshold Logic Design</i>	Operates transistors below the threshold voltage to minimize dynamic and leakage power.	Significantly reduces power consumption but slows down processing.	Low-speed sensing.
<i>Dynamic Voltage and Frequency Scaling (DVFS)</i>	Adjusts voltage and frequency based on real-time workload, scaling down during low activity periods.	Reduces both dynamic and static power by lowering frequency and voltage when full performance is not needed.	Processing units in IoT hubs.
<i>Clock Gating and Power Gating</i>	Disables clock signals or power to parts of the circuit when not in use to conserve energy.	Cuts off power or disables clock in idle states.	Communication modules, MCUs.
<i>Multi-Vth and Multi-Vdd Design</i>	Utilizes different threshold voltages and supply voltages in different parts of the circuit to optimize power and performance.	Reduces power in low-performance areas of the system.	Mixed-performance IoT systems.
<i>Duty Cycling</i>	Puts components into low-power or sleep modes.	Minimizes energy waste by only operating the components when necessary.	Environmental sensors, IoT edge devices.
<i>Energy Harvesting Integration</i>	Incorporates energy scavenging from ambient sources like solar, RF, or vibration to reduce reliance on traditional power sources.	Supplements power needs, especially for devices in remote areas or with limited battery capacity.	Remote IoT devices, environmental monitors

4. Harvesting Techniques for IoT Devices

Energy harvesting is an essential technique for extending the operational lifetime of IoT devices, especially those deployed in remote or hard-to-reach locations where battery replacement is difficult or impractical. By collecting energy from ambient sources like light, vibration, thermal gradients, and radio frequency (RF) signals, energy-harvesting systems can either supplement or completely replace traditional battery-powered systems.

4.1. Solar Energy Harvesting

Solar energy is one of the most widely used sources of power for IoT devices. Photovoltaic (PV) cells convert sunlight into electrical energy, making them ideal for outdoor applications. Solar energy harvesting can be highly efficient when there is sufficient sunlight, but its effectiveness diminishes in indoor environments or during night time. Solar-powered IoT systems are commonly used in smart agriculture, environmental monitoring, and outdoor sensor networks.

4.2. Vibration/Mechanical Energy Harvesting

Vibration-based energy harvesting, also known as piezoelectric energy harvesting, converts mechanical vibrations into electrical energy using piezoelectric materials. This method is suitable for environments with constant or intermittent mechanical motion, such as industrial machinery, vehicles, or structures subjected to wind or water flow. IoT devices using vibration energy are often deployed in industrial monitoring applications, where vibrations from machinery can provide a steady energy source.

4.3. Thermal Energy Harvesting

Thermal energy harvesting utilizes temperature differences between two surfaces to generate electricity via thermoelectric generators (TEGs). This technique is particularly effective in industrial settings where significant temperature gradients exist, such as engines, boilers, or power plants. The harvested energy is used to power sensors and monitoring systems that track temperature, pressure, and other critical parameters.

4.4. Radio Frequency (RF) Energy Harvesting

RF energy harvesting captures electromagnetic waves emitted by radio transmitters, Wi-Fi routers, or mobile phone towers and converts them into usable electrical power. Though the amount of energy harvested from RF signals is relatively low, it can be sufficient for ultra-low-power IoT devices, such as passive sensors or RFID tags. RF energy harvesting is especially useful in urban environments where RF signals are ubiquitous.

4.5. Hybrid Energy Harvesting

Many IoT systems incorporate hybrid energy harvesting techniques, combining multiple sources (e.g., solar and vibration) to ensure continuous power supply in diverse environments. Hybrid systems improve reliability by ensuring that when one energy source is unavailable, another can compensate, extending the operational lifetime of the device.

Table 3 Energy source & their challenges

Energy Source	Description	Applications	Advantages	Challenges
Solar Energy Harvesting	Converts sunlight into electrical energy using photovoltaic cells.	Outdoor sensors, smart agriculture, environmental monitoring.	High efficiency in sunlight, reliable outdoors.	Limited by indoor use, weather conditions, and night time.
Vibration/Mechanical Energy Harvesting	Uses piezoelectric materials to convert mechanical vibrations into electrical energy.	Industrial machinery, vehicles, bridges, infrastructure.	Suitable for environments with constant motion.	Energy availability depends on mechanical activity.
Thermal Energy Harvesting	Generates electricity from temperature differences using thermoelectric generators (TEGs).	Industrial equipment, power plants, engines.	Effective in high-temperature environments.	Requires significant temperature gradients.
Radio Frequency(RF) Energy Harvesting	Captures electromagnetic waves from radio Transmitters, Wi-Fi routers.	Passive sensors, RFID tags, urban IoT networks.	Useful in RF-rich environments, no direct power source needed.	Low energy output, limited range and efficiency.

5. Case Studies of Energy-Efficient IoT Devices

Energy efficiency is critical to the success of IoT devices, particularly those deployed in remote or resource-constrained environments. Several innovative IoT devices have demonstrated remarkable energy efficiency through the integration of low-power design techniques and energy-harvesting methods. Below are some real-world case studies of energy-efficient IoT devices:

5.1. Smart Agriculture Sensor Nodes

In modern smart agriculture systems, IoT sensor nodes are deployed to monitor environmental conditions such as soil moisture, temperature, humidity, and light intensity. These sensor nodes typically operate on batteries and incorporate various low-power design techniques such as duty cycling and dynamic voltage and frequency scaling (DVFS) to reduce energy consumption. Additionally, some systems utilize solar energy harvesting to supplement the power supply, extending the operational life span of the sensors. The Libelium Wasp mote is a prime example of an energy-efficient sensor platform, offering multiple communication protocols and low-power modes to minimize energy use in smart farming.

5.2. Energy-Efficient Smart Meters

Smart meters for electricity, gas, or water utilities often need to operate continuously for long periods without regular maintenance. To ensure long-term performance, these devices employ energy-efficient communication protocols like Zigbee or LoRa, combined with power-efficient microcontrollers that manage metering operations. Many smart meters also integrate low-power wireless transmission to send periodic updates to utility providers. The Itron Open Way Riva

platform, for example, combines advanced metering infrastructure (AMI) with ultra-low-power components, enabling long-term, reliable data transmission while minimizing energy consumption.

5.3. Wearable Health Monitoring Devices

Wearable health devices, such as fitness trackers and medical monitoring tools, must be compact and lightweight while offering extended battery life. Devices like the Fitbit Charge or Apple Watch integrate multiple low-power sensors (heart rate, motion, temperature) and use efficient power management algorithms to achieve extended operation. In addition to their low-power design, these wearables also feature energy-efficient wireless communication (Bluetooth Low Energy, BLE) for synchronizing data with smartphones, which further conserves battery power.

5.4. Remote Environmental Monitoring Stations

Remote environmental monitoring systems are often deployed in isolated areas to track parameters such as air quality, water levels, or wildlife activity. These systems are designed with energy-harvesting capabilities such as solar panels or wind turbines, ensuring continuous operation without the need for manual power replenishment. One notable example is the Libelium Plug & Sensor device, which integrates solar energy harvesting to support long-term environmental monitoring with ultra-low-power operation.

5.5. Smart Lighting Systems

Smart lighting systems are designed to optimize power consumption by adjusting light intensity based on ambient conditions or user presence. These systems often use low-power microcontrollers and communication protocols such as Zigbee or Bluetooth Low Energy (BLE).

Table 4 Case study & their application domain

Case Study	Description	Energy-Efficient Techniques Used	Application Domain
Smart Agriculture Sensor Nodes	Sensor nodes deployed for monitoring environmental factors like soil moisture, temperature, and humidity.	Duty cycling DVFS Solar energy harvesting.	Smart farming and precision agriculture.
Energy- Efficient Smart Meters.	Continuous monitoring devices for electricity, gas, or water usage in smart utility systems.	Low-power Communication protocols (Zigbee, LoRa)	Utility monitoring and smart grids.
Wearable Health Monitoring Devices	Wearables for tracking health metrics like heart rate, motion, and temperature in real-time.	Low-power sensors Power-efficient communication (BLE).	Fitness tracking, healthcare devices.
Remote Environmental Monitoring Stations	Remote systems designed to monitor environmental conditions in isolated areas.	Solar energy harvesting Ultra-low-power operation	Environmental and wildlife monitoring

6. Challenges and Open Research Areas

Despite significant advancement in energy-efficient IoT design, several challenges and open research areas remain:

6.1. Energy Harvesting Limitations

While energy harvesting is promising, there are challenges regarding energy storage, power management, and efficiency under variable environmental conditions. More research is required to improve the effectiveness of hybrid harvesting systems and ensure stable power supply in diverse climates and locations.

6.2. Power Consumption versus Performance Trade-off

Techniques like sub-threshold logic reduce power consumption but at the expense of processing speed. Balancing energy efficiency with performance is an ongoing challenge, particularly for real-time applications where high computational power is required.

6.3. Security and Privacy

Energy-efficient designs must also consider security, as encryption and data protection mechanisms often require additional power. Research is needed on designing low-power, secure architectures for IoT devices, especially in sensitive areas like healthcare and industrial monitoring.

6.4. Scalability

As the IoT ecosystem grows, scaling energy-efficient designs to support large networks of interconnected devices presents a challenge. Research in to ultra-low-power protocols and energy-efficient edge computing can help alleviate this issue.

6.5. Standardization

The lack of universal standards for low-power design across different IoT devices and platforms creates inefficiencies. Developing standardized energy-efficient architectures and communication protocols will be critical for the future of IoT systems.

7. Conclusion

The significance of ongoing progress in energy-efficient circuit design for IoT devices cannot be understated. As IoT systems spread across industries and play an increasingly important role in smart cities, healthcare, agriculture, and other applications, the demand for sustainable, energy-efficient solutions will only increase. To realize the vision of a fully interconnected, smart world, research into minimizing power use, enhancing energy harvesting systems, and tackling the difficulties is critical.

Finally, advances in low-power IoT design will contribute not only to longer-lasting devices but also to lowering the environmental impact of millions of deployed devices worldwide. By pushing the bounds of energy efficiency, we can ensure that IoT technology evolves sustainably, enabling smarter, greener, and more connected systems in the future

Compliance with ethical standards

Disclosure of conflict of interest

The authors have no conflicts of interest to declare.

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