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A Comprehensive Review Of Energy-Efficient Circuit Design Techniques For Internet Of Things (IoT) Devices

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ABSTRACT
The Internet of Things (IoT) is expanding at a rapid pace, which has increased demand for devices that can function under strict power and energy limits. To satisfy the demands of long-term operation, energy-efficient circuit design has emerged as a crucial field of study, particularly for battery-powered and energy-harvesting Internet of Things devices. This study provides an extensive overview of the most recent developments in energy-efficient circuit design methods for Internet of Things devices. It examines several low-power design techniques, such as energy harvesting technologies, dynamic voltage and frequency scaling (DVFS), sub-threshold logic, and sleep mode techniques. The study also investigates how ultra-low-power processors, communication modules, and sensors might improve the overall energy efficiency of Internet of Things systems. Key challenges such as maintaining performance under limited energy budgets, minimizing leakage power, and optimizing trade-offs between power, performance, and area are discussed. The review also highlights recent trends and future research directions aimed at further reducing energy consumption while ensuring reliable and scalable IoT deployments.

Keywords: Internet of Things (IoT); Dynamic Voltage and Frequency Scaling (DVFS)

Introduction

The seamless integration of physical items with the internet is made possible by the Internet of Things (IoT), which is completely changing how we interact with our surroundings. IoT devices are becoming essential to modern life, from smart homes and industrial automation to environmental sensing and healthcare monitoring. But as the number of IoT devices keeps increasing at an exponential rate, energy consumption has become a big problem. In order to assure long-term, autonomous functioning, the majority of Internet of Things devices must have extremely energy-efficient designs because they run on finite power sources like batteries or energy-harvesting systems.

As a means of prolonging battery life and mitigating the environmental impact of the millions of IoT devices that are being deployed worldwide, energy-efficient circuit design has emerged as a key component in solving these concerns. IoT applications that need to utilize the least amount of energy possible while still functioning cannot be served by traditional circuit design methods, which put performance first. Therefore, in order to address the energy limits of Internet of Things systems without sacrificing functionality or dependability, scientists and engineers are concentrating on developing novel design approaches and cutting-edge technologies.

An extensive overview of the best energy-efficient circuit design methods for Internet of Things devices is given in this study. It discusses low-power design techniques like clock gating, dynamic voltage and frequency scaling (DVFS), sub-threshold operation, and sleep modes. To further improve the energy efficiency of IoT networks, it also looks at how energy harvesting methods and ultra-low-power sensors can be integrated. The objective of this review is to provide valuable insights for researchers and practitioners who wish to advance the development of sustainable IoT technologies by highlighting the main challenges, trade-offs, and opportunities in designing energy-efficient circuits for IoT devices through a synthesis of recent advancements in the field.

Power Consumption in IoT Devices

The power consumption of IoT devices is a crucial factor in determining their operational longevity, especially for battery-powered or energy-harvesting systems. IoT devices typically consist of three primary components: sensors, communication modules, and processing units. Each of these components contributes differently to the overall power profile of the device, depending on factors such as data transmission frequency, sensing activities, and computation complexity.

1. Sensors

Sensors in IoT devices monitor environmental conditions like temperature, pressure, motion, or humidity. These components usually consume minimal power during active sensing but can significantly contribute to the overall energy consumption if they remain in continuous operation. Many IoT systems implement duty cycling, where the sensor is periodically powered down to save energy, or event-driven sensing, where the sensor activates only when a significant event occurs.

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2. Communication Modules

Wireless communication is one of the most energy-intensive operations in IoT devices. Sending data wirelessly, especially over long distances, consumes considerable power. Communication protocols like Wi-Fi, Bluetooth Low Energy (BLE), Zigbee, and LoRa offer varying trade-offs between range, data rate, and power consumption. Protocols designed specifically for low-power IoT networks, such as BLE and Zigbee, are optimized to reduce the energy required for transmitting data.

3. Processing Units

The microcontroller or processor manages the device's operations, including data processing, communication, and sensor management. Power consumption in the processing unit depends on the computational complexity of the tasks, frequency of operation, and the power management techniques employed. Ultra-low-power microcontrollers are often used in IoT devices to minimize energy consumption during data processing. Techniques like dynamic voltage and frequency scaling (DVFS) further reduce power usage by adjusting the processor's frequency and voltage based on workload demands.

Table 1. Components& their Power consumption characteristics

Component	Description	Power Consumption Characteristics
Sensors	Responsible for collecting data from the environment (e.g., temperature, humidity, motion sensors).	- Low power during active sensing, but continuous operation can drain power. - Techniques like duty cycling and event-driven sensing are used to reduce power consumption.
Communication Modules	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, especially during idle periods.
Processing Units	Microcontroller (MCU) or processor that controls operations and manages tasks like data processing and communication.	- Power usage depends on computational load. - Techniques like DVFS adjust voltage and frequency to save power during low-demand operations. - Ultra-low-power MCUs.
Power Management (Modes)	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. - Effective mode transitions are crucial for long battery life.
Battery/Energy Harvesting	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. - Energy-harvesting technologies supplement power and reduce reliance on traditional batteries.

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:

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.

2. Dynamic Voltage and Frequency Scaling (DVFS)

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

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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. 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.

4. Multi-Vth and Multi-Vdd Design Techniques

Multi-Vth (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-Vdd (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.

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.

6. Energy Harvesting Integration

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
Sub-Threshold Logic Design	Operates transistors below the threshold voltage to minimize dynamic and leakage power.	- Significantly reduces power consumption but slows down processing. - Ideal for low-speed, low-power IoT applications.	Low-speed sensing, wearables
Dynamic Voltage and Frequency Scaling (DVFS)	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
Clock Gating and Power Gating	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, saving dynamic and leakage power.	Communication modules, MCUs
Multi-Vth and Multi-Vdd Design	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 while maintaining performance where necessary.	Mixed-performance IoT systems
Duty Cycling	Puts components into low-power or sleep modes when not in use, waking them up periodically for operation.	- Minimizes energy waste by only operating the components when necessary.	Environmental sensors, IoT edge devices
Energy Harvesting Integration	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

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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.

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 nighttime. Solar-powered IoT systems are commonly used in smart agriculture, environmental monitoring, and outdoor sensor networks.

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.

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. **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.

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 nighttime.
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, or mobile towers.	Passive sensors, RFID tags, urban IoT networks.	Useful in RF-rich environments, no direct power source needed.	Low energy output, limited range and efficiency.
Hybrid Energy Harvesting	Combines multiple energy sources (e.g.,	Remote monitoring, environmental	Improves reliability and ensures	Increased complexity,

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	solar, vibration, thermal) to maximize power availability.	sensors, IoT devices in diverse environments.	continuous power.	higher cost and integration challenges.

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:

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 lifespan of the sensors. The Libelium Waspmote 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.

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

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.

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 & Sense! device, which integrates solar energy harvesting to support long-term environmental monitoring with ultra-low-power operation.

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). The Philips Hue system, for example, allows users to control lighting remotely, automatically dimming or turning off lights when not needed. This reduces energy consumption significantly while still offering convenience and functionality.

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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) - Energy-efficient microcontrollers - Power gating	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) - Optimized power management algorithms	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
Smart Lighting Systems	Intelligent lighting systems that adjust based on ambient light and occupancy.	- Low-power microcontrollers - Zigbee, BLE communication - Automated dimming for power savings	Smart homes and buildings

Challenges and Open Research Areas

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

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.

2. **Power Consumption vs. 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.

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.

4. **Scalability**:

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

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.

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.

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