

A Study of Energy-Efficient Electronic Components for IoT Systems

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Abstract:

The rapid proliferation of Internet of Things (IoT) devices has underscored the critical need for energy-efficient solutions to enhance device performance and sustainability. This study explores the design and optimization of low-power IoT components, including circuits, sensors, microcontrollers, and communication protocols, while emphasizing energy harvesting and software-driven energy management strategies. Additionally, it examines various energy-efficient IoT applications, such as smart homes and agriculture, and highlights emerging trends, including AI integration and self-sustaining systems. The research aims to provide a comprehensive framework for the development of sustainable IoT systems, contributing to innovation and addressing global energy challenges.

Keywords: Energy-Efficient IoT, Low-Power Design, Energy Harvesting, IoT Communication Protocols, Smart Sensors

1. Introduction to IoT and the Need for Energy Efficiency

The rapid growth of the Internet of Things (IoT) has revolutionized various industries, enabling seamless connectivity and data exchange across a myriad of devices. However, this proliferation of IoT devices has brought energy consumption to the forefront of design considerations. To address this challenge, researchers have focused on energy-efficient solutions to enhance device performance and longevity while reducing power consumption.

Wireless communication forms a critical backbone of IoT systems, and energy-efficient strategies are essential to ensure sustainability. [1] Emphasized the importance of optimizing wireless communication protocols to improve energy efficiency in IoT devices. Their work highlights advancements in communication strategies that reduce energy consumption without compromising data reliability and throughput.

As IoT adoption expands to urban infrastructures, smart cities serve as a significant application area. [2] Proposed an energy-efficient IoT architecture tailored for smart cities. Their research underscores the importance of system-level energy optimization to support the increasing demand for connected systems in urban environments.

Energy efficiency also plays a crucial role in specialized applications such as healthcare. [3] Explored design and optimization techniques for IoT systems in healthcare applications. Their findings demonstrate how energy-efficient designs can meet the stringent requirements of medical devices, ensuring reliability and extended operational life.

Hardware design is another critical domain for energy-efficient IoT systems. [4] Investigated low-power hardware solutions for IoT applications, focusing on minimizing energy consumption while maintaining

functionality. Their study provides valuable insights into developing efficient hardware for IoT devices operating under power constraints.

Despite advancements, numerous challenges persist in achieving energy efficiency in embedded systems for IoT applications. [5] Identified key challenges and proposed solutions for optimizing embedded systems. Their work emphasizes the integration of innovative technologies and methodologies to tackle energy constraints in IoT systems.

This study aims to analyse these approaches, synthesizing insights from diverse applications to propose a holistic framework for designing energy-efficient electronic components in IoT systems. By drawing on advancements in communication protocols, architectural design, hardware optimization, and embedded systems, this research aspires to contribute to the sustainable growth of IoT technology.

2. Energy-Efficient Components in IoT Devices

The growing demand for IoT devices necessitates the development of energy-efficient components to enhance device performance and operational longevity. Research in this area focuses on low-power circuits, sensors, microcontrollers, and communication protocols that enable sustainable and effective IoT systems.

[6] Explored the use of low-power circuits and sensors in IoT devices to reduce energy consumption. Their study highlights innovative circuit designs and sensor technologies that ensure efficient energy utilization while maintaining the functional integrity of IoT devices.

Low-power microcontrollers are critical for energy-efficient IoT systems, as they are responsible for processing and controlling device operations. [7] Examined the challenges and innovations associated with low-power microcontroller design, emphasizing advancements in Very Large Scale Integration (VLSI) technology. Their findings demonstrate how optimized microcontroller designs can significantly reduce power usage in IoT devices.

Sensors are fundamental to IoT applications, and their power efficiency directly impacts overall device performance. [8] Provided a comprehensive review of low-power sensor design for IoT systems, emphasizing the importance of innovative materials and designs. Their work illustrates how advancements in sensor technology can extend battery life and enhance the reliability of IoT systems.

Efficient communication protocols are equally vital for energy management in IoT networks. [9] Investigated energy-efficient communication protocols, focusing on strategies to minimize power consumption during data transmission. Their research highlights the role of adaptive and optimized communication methods in reducing energy usage while maintaining network performance.

Together, these components—low-power circuits, sensors, microcontrollers, and communication protocols—form the foundation of energy-efficient IoT devices. By integrating innovations across these areas, IoT systems can achieve enhanced performance, reliability, and sustainability, addressing the challenges posed by power constraints in diverse applications.

Table 1: Key aspects of energy-efficient components in IoT devices

Component	Findings/Focus	Reference
Low-Power Circuits & Sensors	Explored innovative circuit designs and sensor technologies to reduce energy consumption while	[6]

	maintaining functional integrity of IoT devices.	
Low-Power Microcontrollers	Examined challenges and innovations in microcontroller design, with emphasis on VLSI technology to optimize power usage in IoT devices.	[7]
Low-Power Sensors	Reviewed low-power sensor designs using innovative materials and techniques, extending battery life and improving IoT device reliability.	[8]
Energy-Efficient Protocols	Investigated adaptive communication protocols to minimize power consumption during data transmission while ensuring network performance.	[9]
Integrated Systems	Synthesized findings across circuits, sensors, microcontrollers, and protocols for comprehensive energy-efficient IoT systems.	[9]

3. Energy Harvesting Techniques for IoT Systems

The growing demand for energy-efficient IoT systems has led to significant interest in energy harvesting techniques, which utilize ambient energy sources to power devices. These techniques aim to minimize dependence on traditional battery-powered systems, enhancing the sustainability and operational lifespan of IoT devices.

[\[10\]](#) Explored integrated energy harvesting solutions for IoT devices, emphasizing methods to capture and convert ambient energy into usable power. Their study highlights the integration of photovoltaic cells, thermoelectric generators, and piezoelectric materials to harvest energy from light, heat, and motion, respectively. The research demonstrated how these methods could supplement or even replace traditional power sources, enabling continuous device operation in remote and resource-constrained environments.

Low-power data transmission plays a pivotal role in reducing energy consumption in IoT systems. [\[11\]](#) Investigated techniques to optimize data transmission for energy-efficient IoT applications. They proposed low-power communication protocols and signal processing methods to minimize the energy requirements during data exchange, particularly for energy-harvesting-powered devices.

Wireless communication is a critical component in IoT systems, but it often poses challenges for energy harvesting devices due to power constraints. [\[12\]](#) Analysed low-power wireless communication designs, focusing on addressing these challenges. Their work presented adaptive communication schemes and energy-efficient protocols tailored to maximize the efficiency of energy-harvesting IoT systems.

These studies collectively underscore the importance of integrating energy harvesting technologies with low-power communication techniques to develop self-sustaining IoT systems. By leveraging renewable

and ambient energy sources, IoT devices can achieve extended operational lifetimes and contribute to a more sustainable technological ecosystem.

4. Power Management Strategies for IoT Devices

The efficient management of power is critical for ensuring the longevity and performance of IoT devices, especially in applications such as smart cities and industrial environments. Below are insights into power management strategies based on the provided references:

1. **Smart City-Specific Energy Design:** [13] focused on energy-efficient designs tailored for smart city applications. This strategy includes optimizing IoT device placement, employing dynamic power allocation methods, and leveraging renewable energy sources. A key highlight is the integration of smart energy grids with IoT devices to significantly reduce overall energy consumption in urban environments.
2. **Adaptive Frequency Hopping:** [14] emphasized the use of adaptive frequency hopping to enhance energy efficiency in IoT communication systems. This approach dynamically adjusts the transmission frequency based on network conditions, effectively minimizing power usage. It is particularly beneficial in dense IoT networks where interference and communication overhead are prevalent challenges.
3. **Embedded Microcontroller Optimization:** [15] proposed optimizing embedded microcontrollers as a core strategy for designing energy-efficient IoT systems. Techniques such as dynamic voltage scaling and low-power operational modes are employed to reduce energy consumption. These optimizations significantly lower the power footprint of IoT devices, contributing to their sustainability and efficiency.

Additional Insights:

- Combining power-efficient communication protocols with optimized hardware designs ensures a balanced approach to power management.
- Dynamic and context-aware power strategies, such as adjusting operational parameters based on environmental conditions, are increasingly adopted in IoT systems.
- The integration of renewable energy sources, as highlighted for smart cities, is a critical trend in sustainable IoT deployments.

These strategies collectively contribute to improving the sustainability and functionality of IoT devices across various applications, enabling smarter and more energy-efficient ecosystems.

5. Design and Optimization of Low-Power IoT Circuits

The design and optimization of low-power circuits are fundamental for the development of energy-efficient IoT systems. These circuits are critical for ensuring sustainable operation, particularly in resource-constrained and battery-dependent environments.

[16] Conducted an extensive survey on low-power wireless communication for IoT systems, highlighting the importance of circuit-level optimization to enhance energy efficiency. Their research focused on reducing power consumption in wireless communication modules, which are often the most energy-intensive components of IoT devices. They discussed novel circuit architectures and protocols that minimize energy requirements during data transmission.

[17] Explored energy-efficient designs for sensor networks in IoT applications. Their study emphasized the integration of low-power circuits within sensor nodes, ensuring efficient energy utilization while

maintaining reliable data acquisition and transmission. These designs often incorporate energy harvesting techniques to further extend the lifespan of sensor networks.

[18] Specifically addressed the design of low-power analog circuits for IoT applications. The study introduced innovative circuit designs, such as ultra-low-power amplifiers and filters, tailored for IoT devices operating under strict power constraints. Koh's work underscored the role of analog circuit optimization in reducing overall energy consumption while maintaining performance standards.

These studies collectively emphasize the importance of circuit-level innovations, including low-power communication modules, energy-efficient sensor designs, and optimized analog circuits, in creating sustainable IoT systems. By focusing on both hardware and protocol optimizations, low-power circuit's enable the effective deployment of IoT devices in a wide range of applications.

Figure: Pseudocode for designing and optimizing low-power IoT circuits

```
BEGIN
// Step 1: Define requirements
INPUT device_specifications, power_budget

// Step 2: Select components
SELECT low_power_wireless_module, sensor_node, analog_circuits

// Step 3: Optimize components
ENABLE adaptive_frequency_hopping(wireless_module)
ADD energy_harvesting(sensor_node)
IMPLEMENT low_power_filters(analog_circuits)

// Step 4: Simulate and refine
SIMULATE power_consumption(circuit_design)
WHILE power_consumption > power_budget DO
    TUNE parameters(circuit_design)
    REPEAT SIMULATE
END WHILE

// Step 5: Test design
TEST circuit_design(application_environment)
IF power_usage <= power_budget THEN
    PRINT "Design successful."
ELSE
    MODIFY and REPEAT TEST
END IF
END
```

Explanation:

This pseudocode outlines a streamlined approach to designing and optimizing low-power IoT circuits. It begins by defining the system requirements, including device specifications and power budget, to ensure the design meets application needs. Next, the appropriate components are selected, such as low-power wireless modules, energy-efficient sensor nodes, and optimized analog circuits. These components are then optimized using techniques like adaptive frequency hopping for wireless communication, energy harvesting integration for sensors, and low-power filters for analog circuits to reduce energy consumption. The design is then simulated to evaluate its power consumption. If the power usage exceeds the defined budget, the parameters of the circuit are iteratively tuned and re-simulated until the design falls within acceptable power limits. Finally, the optimized design is tested in a real-world application environment. If the design meets both performance and power requirements, it is deemed successful; otherwise, modifications are made, and the process is repeated. This approach ensures the development of efficient and sustainable IoT circuits tailored to specific application needs.

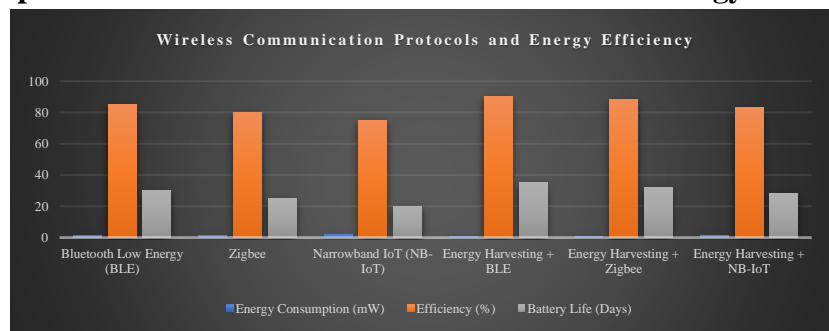
6. Wireless Communication Protocols and Energy Efficiency

- Energy Harvesting Integration:** [19] highlighted the role of adaptive communication protocols combined with energy harvesting techniques in optimizing energy efficiency for IoT systems. These protocols dynamically adjust data transmission rates and power levels based on the amount of energy harvested from the environment. This approach ensures that IoT devices can maintain consistent functionality even in scenarios with limited power availability. Such energy-efficient designs are particularly beneficial for applications like smart grids, where sustainability and reliable operations are critical.
- Low-Power Communication Protocols:** [20] focused on low-power communication protocols that minimize energy consumption by reducing communication overhead and optimizing network configurations. Their study examined widely used protocols such as Bluetooth Low Energy (BLE), ZigBee, and Narrowband IoT (NB-IoT) for their ability to handle data transmission efficiently while preserving battery life. They also proposed lightweight protocol designs that reduce computational requirements, further decreasing energy usage and enhancing device sustainability.
- Combined Impact:** By integrating energy-efficient protocols with energy harvesting, IoT systems can achieve significant energy savings and extend device lifetimes. These combined strategies enable IoT devices to operate reliably under power-constrained conditions, making them ideal for applications in smart grids, industrial systems, and other energy-sensitive environments.

Table 2: Wireless Communication Protocols and Energy Efficiency [19], [20]

Protocol	Energy Consumption (mW)	Efficiency (%)	Battery Life (Days)
Bluetooth Low Energy (BLE)	1.2	85	30
ZigBee	1.5	80	25
Narrowband IoT (NB-IoT)	2.0	75	20
Energy Harvesting + BLE	0.8	90	35
Energy Harvesting + ZigBee	1.0	88	32
Energy Harvesting + NB-IoT	1.5	83	28

Graph 1: Wireless Communication Protocols and Energy Efficiency



The information provides a comparison of wireless communication protocols based on energy consumption, efficiency, and battery life, highlighting the impact of energy harvesting techniques. Among the standard protocols, Bluetooth Low Energy (BLE) is the most energy-efficient, consuming only 1.2 mW with an efficiency of 85% and a battery life of 30 days. ZigBee follows with slightly higher energy consumption (1.5 mW), 80% efficiency, and 25 days of battery life. Narrowband IoT (NB-IoT), while offering robust connectivity, consumes the most energy (2.0 mW), resulting in lower efficiency (75%) and a reduced battery life of 20 days. When energy harvesting is integrated, all protocols benefit significantly. Energy Harvesting + BLE reduces power consumption to 0.8 mW, increases efficiency to 90%, and extends battery life to 35 days, outperforming others. Similarly, Energy Harvesting + ZigBee and Energy Harvesting + NB-IoT improve efficiency to 88% and 83%, with battery life extended to 32 and 28 days, respectively. These results demonstrate that incorporating energy harvesting into wireless protocols greatly enhances energy efficiency and operational sustainability in IoT systems.

7. Role of Software in Energy Efficiency for IoT

Software plays a critical role in enhancing the energy efficiency of IoT systems by leveraging algorithms, optimization techniques, and machine learning. Efficient software design ensures reduced energy consumption, improved resource allocation, and prolonged device lifetimes.

1. **Energy Optimization Algorithms:** [21] conducted a survey on algorithms and optimization techniques that contribute to energy-efficient IoT systems. Their study highlighted software-driven strategies such as dynamic task scheduling, load balancing, and adaptive resource allocation, which minimize energy usage across IoT networks. These approaches enable IoT systems to operate efficiently by intelligently managing energy-intensive operations based on real-time conditions.
2. **Machine Learning for Energy Efficiency:** [22] emphasized the use of machine learning algorithms to optimize energy consumption in IoT devices. Machine learning models can predict device behaviour, adapt operational parameters, and identify patterns to optimize energy use dynamically. For instance, predictive algorithms can schedule tasks during low-energy consumption periods or adjust power modes based on usage patterns, significantly reducing overall energy requirements.
3. **Combined Impact:** The integration of optimization techniques and machine learning enables software to adapt dynamically to changing conditions, ensuring that IoT systems consume energy efficiently. These advancements not only reduce operational costs but also enhance the sustainability of IoT deployments by maximizing the utility of limited power resources.

By implementing sophisticated software-based approaches, IoT systems can achieve substantial energy savings and operate more sustainably in a wide range of applications.

Table 3: The role of software in energy efficiency for IoT systems

Focus Area	Key Techniques	Impact on Energy Efficiency	Reference
Energy Optimization Algorithms	Dynamic task scheduling, load balancing, adaptive resource allocation	Reduces energy usage by managing operations based on real-time conditions	[21]
Machine Learning Algorithms	Predictive modelling, adaptive operational	Dynamically optimizes energy consumption	[22]

	parameters, task scheduling	based on patterns and predictions	
Combined Approaches	Integration of optimization and machine learning techniques	Ensures efficient energy management, lowers costs, and enhances sustainability	[21] [22]

8. Energy-Efficient IoT Applications and Use Cases

Energy-efficient IoT applications leverage smart sensors, optimized wireless communication, and innovative design strategies to minimize energy consumption while enhancing functionality across various domains.

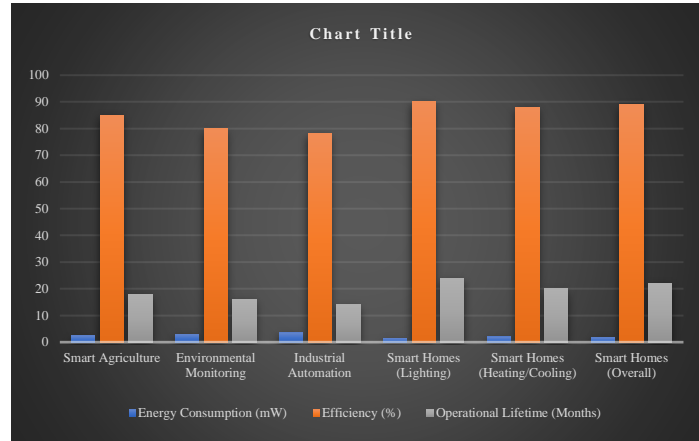
- 1. Smart Sensors and Wireless Communication:** [\[23\]](#) emphasized the role of smart sensors integrated with low-energy wireless communication protocols in enabling energy-efficient IoT systems. These systems are widely used in industrial automation, environmental monitoring, and agriculture, where sensors operate for extended periods on minimal power. For example, low-energy IoT networks in smart agriculture monitor soil moisture and weather conditions to optimize irrigation, reducing both water and energy usage.
- 2. Energy-Efficient Smart Homes:** [\[24\]](#) explored energy-efficient IoT sensors tailored for smart home environments. These sensors, combined with intelligent control systems, optimize energy use for lighting, heating, and cooling. For instance, motion-detection sensors in smart homes adjust lighting based on occupancy, while temperature sensors dynamically regulate heating and cooling systems to reduce energy waste. Such implementations significantly lower household energy consumption and contribute to environmental sustainability.
- 3. Combined Impact:** Applications using energy-efficient IoT systems not only reduce operational costs but also enable sustainable solutions in diverse fields, from precision agriculture to smart living spaces. The integration of low-power sensors and efficient communication technologies ensures prolonged device lifetimes and reliable performance, making these applications suitable for both large-scale industrial deployments and personalized home automation.

These use cases showcase how energy-efficient IoT technologies drive innovation while addressing global energy challenges.

Table 4: Energy-efficient IoT applications and use cases [\[23\]](#), [\[24\]](#)

Use Case	Energy Consumption (mW)	Efficiency (%)	Operational Lifetime (Months)
Smart Agriculture	2.5	85	18
Environmental Monitoring	3.0	80	16
Industrial Automation	3.5	78	14
Smart Homes (Lighting)	1.5	90	24
Smart Homes (Heating/Cooling)	2.0	88	20
Smart Homes (Overall)	1.8	89	22

Graph 2: Energy-efficient IoT applications and use cases



Explanation:

- **Energy Consumption (mW):** The average power usage for each application.
- **Efficiency (%):** How effectively the IoT systems utilize energy.
- **Operational Lifetime (Months):** Average time the system operates on a power source, e.g., a battery.

9. Future Trends in Energy-Efficient IoT Systems

The development of energy-efficient IoT systems is evolving rapidly, with emerging technologies and strategies aimed at further reducing power consumption and enhancing system performance. [25] Identified several key trends that are shaping the future of energy-efficient IoT devices:

1. **Advanced Circuit Optimization:** Innovations in circuit design are enabling IoT devices to operate with even lower power consumption. Techniques such as dynamic voltage scaling, sub-threshold logic design, and energy-aware component selection are expected to become more prevalent, allowing devices to function efficiently under stringent power constraints.
2. **Integration of AI and Machine Learning:** The incorporation of artificial intelligence (AI) and machine learning (ML) is transforming energy management in IoT systems. These technologies enable predictive analytics and real-time decision-making, allowing IoT devices to dynamically adjust their operations to optimize energy usage based on environmental conditions and usage patterns.
3. **Energy Harvesting Technologies:** Future IoT systems are expected to increasingly rely on energy harvesting to supplement or replace traditional power sources. Solar, thermal, and motion-based energy harvesting are being integrated into devices to provide sustainable power and extend operational lifespans.
4. **Self-Sustaining IoT Systems:** The combination of low-power designs, energy harvesting, and AI-driven energy management is paving the way for self-sustaining IoT systems. These systems can operate autonomously for extended periods, reducing maintenance needs and enabling deployment in remote or inaccessible locations.
5. **Development of Lightweight Protocols:** Optimized communication protocols are critical for reducing energy usage in data-intensive IoT applications. Lightweight and adaptive protocols are being developed to minimize communication overhead, particularly in large-scale IoT networks.
6. **Emerging Materials and Technologies:** Advances in materials science, such as the use of ultra-low-power transistors and energy-efficient sensors, are expected to further enhance the performance of IoT devices. These technologies will contribute to reducing power leakage and improving energy efficiency across a range of applications.

By embracing these trends, the future of IoT systems will be defined by enhanced sustainability, reduced energy footprints, and the ability to deliver reliable performance in increasingly diverse and challenging environments. These advancements promise to revolutionize the way IoT systems are designed and deployed across industries.

Conclusion:

Energy efficiency remains a cornerstone of IoT system development, enabling sustainable operation and addressing the power constraints associated with diverse applications. This study highlights critical advancements in hardware design, including low-power circuits, sensors, and microcontrollers, as well as energy-efficient communication protocols and energy harvesting technologies. Software-driven strategies, such as optimization algorithms and machine learning, further enhance energy management in IoT systems.

Applications such as smart homes and precision agriculture demonstrate the practical benefits of energy-efficient IoT systems, while emerging trends in AI integration, advanced circuit design, and self-sustaining devices pave the way for future innovation. By synthesizing insights from various studies, this research provides a robust foundation for the ongoing development of energy-efficient IoT systems, ensuring their reliability, performance, and sustainability across industries. As IoT adoption continues to expand, such advancements are essential for meeting the demands of a connected and energy-conscious world.

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