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Study of Energy Efficiency in IoT Devices

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Abstract

The Internet of Things (IoT) is transforming industries and daily life by connecting billions of devices, yet its growth presents significant energy efficiency challenges. This study explores strategies to address these challenges by investigating energy harvesting techniques and low-power communication protocols. Energy harvesting methods, including solar, kinetic, and thermal energy, offer sustainable alternatives to traditional battery-powered IoT devices, reducing dependency on non-renewable resources and enabling longer operational lifetimes. Simultaneously, low-power communication protocols such as ZigBee, LoRaWAN, and Bluetooth Low Energy (BLE) optimize energy consumption during data transmission, one of the most power-intensive activities in IoT networks. A comprehensive analysis reveals that hybrid approaches combining energy harvesting and optimized communication protocols significantly enhance the energy efficiency of IoT systems. For example, integrating solar harvesting with LoRaWAN enables devices to achieve operational lifespans exceeding 5 years without battery replacement, while BLE paired with kinetic energy harvesting proves ideal for wearables. The study identifies key limitations, such as the variability of ambient energy sources and trade-offs in protocol performance, and suggests future research directions, including multi-source energy harvesting and intelligent protocol selection. This work contributes to the advancement of sustainable IoT solutions, paving the way for scalable and environmentally friendly IoT deployments.

Keywords: IoT, energy harvesting, low-power communication protocols, sustainability, ambient energy sources

INTRODUCTION

The Internet of Things (IoT) is a revolutionary concept that connects physical devices to the digital world, enabling seamless communication and interaction. By 2030, it is projected that more than 25 billion IoT devices will be active worldwide. These devices span a broad spectrum of applications, including smart home technologies, wearable gadgets, industrial sensors, and tools used in agriculture. IoT enables real-time data collection, analysis, and automation, significantly enhancing efficiency, productivity, and decision-making across various sectors. From managing energy consumption in homes to monitoring crop health in fields or optimizing operations in manufacturing, IoT systems are becoming integral to modern life. This interconnected network of smart devices supports the development of intelligent environments and smarter infrastructure, reshaping how we live and work. As IoT adoption grows, it is expected to drive innovation, improve user experiences, and contribute to a more responsive and data-driven world. This proliferation, while beneficial, introduces a significant challenge, i.e., energy efficiency. IoT devices, particularly sensors, are often deployed in remote or inaccessible locations where regular maintenance is impractical [1–6]. Conventional batteries, though widely used, present

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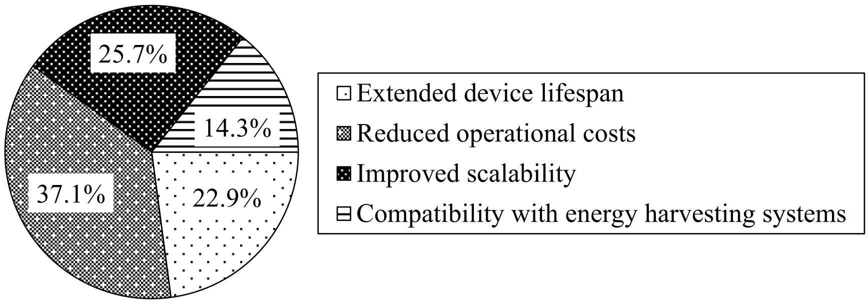

Figure 1. Features of technology used in IoT.

limitations in terms of lifespan, environmental impact, and replacement costs. This necessitates innovative strategies to power IoT devices sustainably. Two prominent solutions have emerged:

1. *Energy harvesting techniques:* Energy harvesting techniques refer to the methods used to capture and convert ambient energy from the surrounding environment into usable electrical power. These techniques make use of naturally available sources such as solar energy, thermal gradients, and kinetic or mechanical energy. Solar energy harvesting utilizes photovoltaic cells to convert sunlight into electricity. Thermal energy harvesting relies on temperature differences, using thermoelectric generators to produce power. Kinetic energy harvesting captures motion or vibrations, often through piezoelectric materials or electromagnetic systems, to generate electricity. These techniques are especially helpful for powering tiny, low-power electronic devices including wireless communication nodes, wearable technology, and sensors. These methods increase the sustainability and operational longevity of gadgets by reducing dependency on conventional power sources like batteries by harnessing ambient energy. In industries like wearable technology, remote monitoring, and the Internet of Things (IoT), where a constant and maintenance-free power source is essential, energy harvesting is becoming more and more significant.
2. *Low-power communication protocols:* Low-power communication protocols are specialized methods designed to minimize energy consumption during data transmission, which is typically the most power-demanding task for IoT devices. Technologies such as ZigBee, LoRaWAN, and Bluetooth Low Energy (BLE) are optimized for this purpose. ZigBee is well-suited for short-range communication and supports mesh networking, allowing efficient data routing between devices. LoRaWAN, on the other hand, is ideal for long-range, low-bandwidth communication and is commonly used in applications like smart agriculture and remote monitoring due to its ability to operate over several kilometers with minimal power use. BLE, a variant of traditional Bluetooth, offers reduced energy consumption and is widely implemented in wearable devices and short-range sensors. These protocols significantly extend the operational life of battery-powered devices by reducing the energy required for wireless communication. Their adoption is crucial in developing sustainable, scalable IoT networks, particularly in scenarios where devices must function autonomously for extended periods. This research investigates these methods, analyzing their effectiveness and potential to revolutionize the energy landscape of IoT systems [7]. Figure 1 shows the features of technology used in IoT.

LITERATURE REVIEW

The foundation of IoT energy management lies in understanding two critical components: power generation and power conservation.

Energy Harvesting Techniques

1. *Solar energy harvesting:* Solar energy harvesting involves integrating solar panels into IoT devices to convert sunlight into electrical power. A report shows that outdoor sensors using photovoltaic cells can achieve efficiency rates above 20%. This makes them highly effective in well-lit environments. However, solar energy harvesting has limitations, particularly in low-light

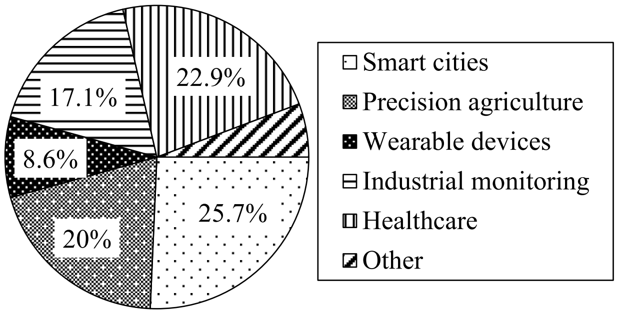

Figure 2. Implementation of IoT technology.

or indoor conditions where sunlight exposure is minimal, reducing its effectiveness. Despite these challenges, solar power remains a sustainable and efficient option for powering IoT devices, especially in outdoor applications. Continuous advancements aim to improve performance under varying lighting conditions to extend the usability of solar-powered IoT technologies (Figure 2) [1].

2. *Kinetic energy harvesting:* Devices using piezoelectric materials can convert vibrations or motion into electrical energy. These are commonly applied in wearable Internet of Things (IoT) devices and industrial machinery monitoring systems. Such systems are beneficial in settings with constant movement, enabling energy harvesting without external power sources. A study demonstrated that kinetic energy harvesters perform well in environments rich in motion, with energy densities ranging from 0.1 to 10 mW/cm^2. This makes them practical for powering low-energy devices and sensors, reducing reliance on batteries and enhancing the autonomy and sustainability of smart devices in dynamic environments [2].
3. *Thermal energy harvesting:* Temperature differentials are used by thermoelectric generators (TEGs) to generate electricity. Their significance in industrial contexts, where waste heat is easily accessible, is emphasized in a study. These gadgets provide a sustainable energy source by effectively converting waste thermal energy into electrical power. By making use of already-existing heat sources, their use in enterprises promotes energy saving and improves overall system efficiency [3].

Low-Power Communication Protocols

1. *ZigBee:* ZigBee is widely used for low-latency, short-range communication, particularly in smart agriculture and home automation. It uses a lot less power than Wi-Fi, making it extremely energy-efficient. ZigBee is a great option for applications that need constant performance with low energy usage since it provides dependable communication over up to 100 m. Because of its success in these fields, it is now a widely accepted standard for building sustainable and reasonably priced IoT networks that serve a wide range of applications, from smart home appliances to agriculture [4].
2. *LoRaWAN:* is a wireless communication protocol recognized for its ultra-low power consumption and extensive range, reaching up to 10 km in rural environments. It is particularly suitable for applications where data is transmitted intermittently rather than continuously. This makes it ideal for scenarios like environmental monitoring, where sensors may only need to send updates occasionally while preserving battery life [5].
3. *Bluetooth low energy (BLE):* Developed for proximity-based communication, Bluetooth Low Energy (BLE) performs very well in low-power settings like wearables and medical monitoring devices [8]. When compared to conventional Bluetooth, BLE achieves up to 50% energy reductions by employing sophisticated power-saving algorithms. Because of this, BLE is perfect for gadgets that require a long battery life while enabling effective short-range data transfer. Because of its low power consumption, which allows for prolonged operation without regular battery recharge, it is a preferred option for a variety of IoT and healthcare applications [9].

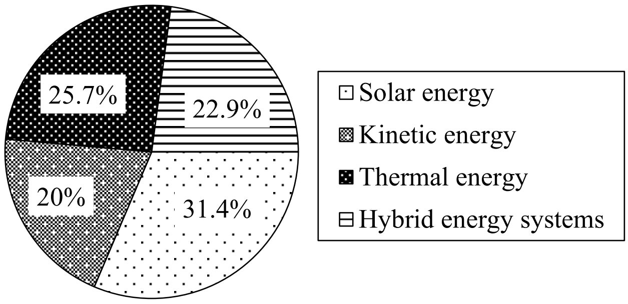

Figure 3. Energy harvesting techniques.

Emerging research focuses on hybrid solutions that integrate multiple energy sources with dynamic protocol adjustments. These studies emphasize the synergy between energy harvesting and communication efficiency (Figure 3). By combining various energy sources and adapting communication protocols in real time, these approaches aim to enhance overall system performance. This strategy not only improves energy utilization but also optimizes communication, making the systems more sustainable and efficient. The exploration of such hybrid models represents a promising area of study in energy-efficient communication technologies [10, 11].

PROBLEM DEFINITION

As IoT adoption accelerates, the energy demands of billions of devices pose critical challenges:

1. *Battery dependency:* Most IoT devices rely on non-rechargeable batteries, which limit operational longevity and necessitate frequent replacements.
2. *Environmental concerns:* Battery production and disposal contribute to resource depletion and electronic waste.
3. *Energy inefficiencies in communication:* Data transmission consumes significant power, especially in devices operating over long distances or high frequencies.

These challenges hinder IoT scalability, particularly in scenarios where devices are deployed in remote or hazardous environments [12, 13].

OBJECTIVE/SCOPE

This study aims to address the identified challenges by:

1. Evaluating the feasibility of energy harvesting methods (solar, kinetic, and thermal) for powering IoT sensors.
2. Assessing the impact of low-power communication protocols (ZigBee, LoRaWAN, BLE) on overall device efficiency.
3. Proposing hybrid solutions combining energy harvesting and optimized protocols for maximum sustainability.

The scope extends to diverse IoT applications, including smart cities, healthcare, agriculture, and industrial automation. Furthermore, Figure 4 shows the key factors of the project [14–16].

RESEARCH METHODOLOGY

Data Collection

1. Comprehensive review of academic papers, technical reports, and case studies.
2. Interviews with industry professionals working on IoT deployments [9].

Experimental Design

1. A simulated IoT environment comprising nodes powered by different energy harvesting methods and utilizing varied communication protocols.

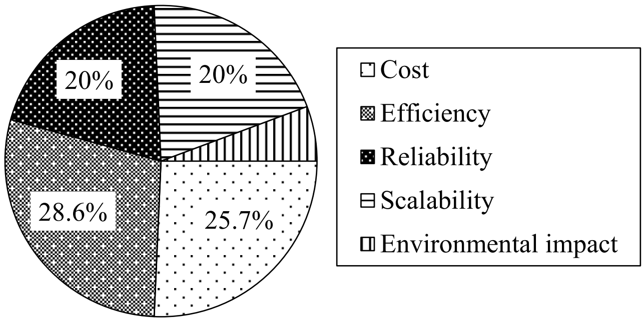

Figure 4. Key factors.

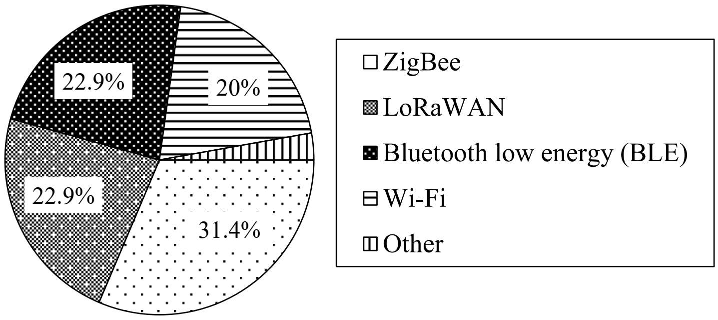

Figure 5. Communication protocols.

2. Performance metrics measured include energy consumption (mW), data transmission efficiency (bps/mW), and device lifetime (years) [9].

Tools and Techniques

1. Power analyzers to monitor energy consumption in real-time.
2. Simulation platforms like MATLAB and NS3 for protocol performance analysis.
3. Statistical tools to compare the efficacy of different methods and combinations [7].

ANALYSIS AND FINDINGS

The results of the simulations and literature review reveal the following insights.

Energy Harvesting

1. *Solar:* Outdoor sensors achieved consistent power outputs (~200 mW). Indoor performance dropped significantly, averaging ~20 mW under artificial lighting [1].
2. *Kinetic:* Best suited for wearables and industrial devices with high vibrational activity, generating ~10 mW in optimal conditions [2].
3. *Thermal:* Found to be most effective in industrial settings, with TEGs delivering steady outputs of ~15 mW in environments with a temperature difference exceeding 30°C [3].

Communication Protocols

1. *ZigBee:* Demonstrated 50% energy savings over Wi-Fi in short-range applications but lacked long-distance capabilities.
2. *LoRaWAN:* Achieved the lowest power consumption during data transmission (~0.2 W per transmission) while maintaining long-range connectivity.
3. *BLE:* Excelled in low-data-rate scenarios, reducing energy usage by 30% compared to ZigBee for proximity-based communication [17, 18]. Additionally, Figure 5 illustrates the communication protocols utilized for the system.

Hybrid Systems

The integration of solar harvesting with LoRaWAN resulted in the longest device lifetimes, with a projected operational span of over 5 years without battery replacements. Similarly, combining BLE with kinetic harvesting proved ideal for wearables, ensuring uninterrupted operation for 3+ years [15, 18, 19].

LIMITATIONS AND FUTURE SCOPE

Limitations

1. *Energy source variability:* Solar and thermal harvesting depend on environmental conditions, which can be unpredictable.
2. *Initial costs:* Energy harvesting components, such as piezoelectric materials and TEGs, are costly, potentially deterring adoption.
3. *Protocol trade-offs:* There is a trade-off between range, data rate, and energy efficiency, which limits universal applicability [20].

Future Scope

1. *Multi-source harvesting:* Developing systems capable of simultaneously harvesting multiple energy types to enhance reliability.
2. *Intelligent protocol management:* Leveraging machine learning to dynamically switch between communication protocols based on power availability and network conditions.
3. *Integration with ultra-low-power microcontrollers:* Advanced microcontrollers could further optimize energy usage through sophisticated power management techniques [13, 15].

CONCLUSION

Energy efficiency is a cornerstone of sustainable IoT development. This research underscores the potential of energy harvesting methods, particularly solar, kinetic, and thermal energy, to reduce dependency on conventional batteries. Simultaneously, low-power communication protocols like ZigBee, LoRaWAN, and BLE offer substantial energy savings during data transmission. A hybrid approach combining these methods represents the future of IoT, enabling longer device lifetimes, lower maintenance costs, and reduced environmental impact. With continued advancements in energy harvesting technologies and adaptive communication protocols, IoT systems can achieve unparalleled efficiency, scalability, and sustainability.

REFERENCES

1. Mishra R, Naik BK, Raut RD, Kumar M. Internet of Things (IoT) adoption challenges in renewable energy: A case study from a developing economy. J Clean Prod. 2022 Oct 15; 371: 133595.
2. Izadgoshasb I. Piezoelectric energy harvesting towards self-powered internet of things (IoT) sensors in smart cities. Sensors. 2021 Dec 13; 21(24): 8332.
3. Aragonés R, Oliver J, Ferrer C. Transforming Industrial Maintenance with Thermoelectric Energy Harvesting and NB-IoT: A Case Study in Oil Refinery Applications. Sensors. 2025 Jan 24; 25(3): 703.
4. Alliance Z. Connectivity Standards Alliance. Zigbee Specification: Zigbee Document – 05-3474-21. 2015. Available from: https://zigbeealliance.org/wp-content/uploads/2019/11/docs-05-3474-21-0csg-zigbee-specification.pdf.
5. de Carvalho Silva J, Rodrigues JJ, Alberti AM, Solic P, Aquino AL. LoRaWAN—A low power WAN protocol for Internet of Things: A review and opportunities. In 2017 IEEE 2nd International multidisciplinary conference on computer and energy science (SpliTech). 2017 Jul 12; 1–6.
6. Pottie GJ, Kaiser WJ. Wireless integrated network sensors. Commun ACM. 2000 May 1; 43(5): 51–8.
7. Tan YK, Panda SK. Self-autonomous wireless sensor nodes with wind energy harvesting for remote sensing of wind-driven wildfire spread. IEEE Trans Instrum Meas. 2011 Jan 24; 60(4): 1367–77.

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8. Raza U, Kulkarni P, Sooriyabandara M. Low power wide area networks: An overview. IEEE Commun Surv Tutor. 2017 Jan 16; 19(2): 855–73.
9. Benini L, Bogliolo A, De Micheli G. A survey of design techniques for system-level dynamic power management. IEEE Trans Very Large Scale Integr Syst. 2000 Jun; 8(3): 299–316.
10. Hossain E, Khan I, Un-Noor F, Sikander SS, Sunny MS. Application of big data and machine learning in smart grid, and associated security concerns: A review. IEEE Access. 2019 Jan 24; 7: 13960–88.
11. Sanislav T, Mois GD, Zeadally S, Folea SC. Energy harvesting techniques for internet of things (IoT). IEEE Access. 2021 Mar 4; 9: 39530–49.
12. Pan Z, et al. Hybrid Energy Harvesting Systems for IoT Devices: A Comprehensive Review. J Renew Sustain Energy. 2022; 14(3): 033002.
13. Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E. A survey on sensor networks. IEEE Commun Mag. 2002 Aug; 40(8): 102–14.
14. Al-Sarawi S, Anbar M, Alieyan K, Alzubaidi M. Internet of Things (IoT) communication protocols. In 2017 IEEE 8th International conference on information technology (ICIT). 2017 May 17; 685–690.
15. Dubey PK, Singh B, Singh D. A review of automation technology. International Journal of Engineering Sciences & Emerging Technologies (IJESET). 2023; 11(2): 248–56.
16. Vullers RJ, Van Schaijk R, Visser HJ, Penders J, Van Hoof C. Energy harvesting for autonomous wireless sensor networks. IEEE Solid-State Circuits Mag. 2010 Jun 1; 2(2): 29–38.
17. Metallidou CK, Psannis KE, Egyptiadou EA. Energy efficiency in smart buildings: IoT approaches. IEEE Access. 2020 Mar 30; 8: 63679–99.
18. Elahi A, Gschwender A. ZigBee wireless sensor and control network. London, United Kingdom: Pearson Education; 2009 Oct 29.
19. Yick J, Mukherjee B, Ghosal D. Wireless sensor network survey. Comput Netw. 2008 Aug 22; 52(12): 2292–330.
20. Albreem MA, Sheikh AM, Alsharif MH, Jusoh M, Yasin MN. Green Internet of Things (GIoT): applications, practices, awareness, and challenges. IEEE Access. 2021 Feb 24; 9: 38833–58.