Commentary
Volume 14:03, 2025

International Journal of Sensor Networks and Data Communications

ISSN: 2090-4886 Open Access

Sustainable Energy Harvesting For Autonomous WSNs and IoT

Farah Rahman*

Department of Sensor Data Analytics, Bengal Institute of Engineering, Dhaka, Bangladesh

Introduction

The pervasive deployment of wireless sensor networks (WSNs) has revolutionized data collection and monitoring across diverse domains, from environmental surveillance to industrial automation. However, a significant challenge hindering the long-term autonomy and widespread adoption of WSNs is the inherent limitation of conventional battery power sources. This reliance on batteries necessitates frequent replacement or recharging, incurring substantial logistical costs and operational downtime, particularly in remote or inaccessible locations.

To address this critical issue, energy harvesting (EH) technologies have emerged as a transformative solution, promising to enable self-sustaining and perpetual operation of sensor nodes. These technologies harness ambient energy from the environment, converting it into electrical power to replenish sensor node batteries or directly power their operations. This approach liberates WSNs from the constraints of finite power supplies, paving the way for truly autonomous and maintenance-free deployments.

Various energy harvesting techniques are being actively researched and developed, each with its unique principles and suitability for different application scenarios. Among these, solar energy harvesting stands out as a well-established and widely applicable method, leveraging photovoltaic cells to convert sunlight into electricity. This approach is particularly effective in outdoor environments where solar radiation is abundant, enabling sensor nodes to achieve perpetual operation through efficient power management and storage strategies [3].

Thermoelectric energy harvesting, another prominent technique, utilizes the Seebeck effect to convert temperature gradients into electrical energy. This method is especially valuable in environments where waste heat is readily available, such as industrial facilities or near electronic components. By capitalizing on existing temperature differences, thermoelectric generators (TEGs) offer a continuous power source for IoT devices and sensor networks, contributing to energy efficiency and sustainability [2].

Radio frequency (RF) energy harvesting presents a compelling option for scavenging energy from ambient electromagnetic waves, such as those emitted by Wi-Fi routers, cellular base stations, and broadcasting towers. While the power density of RF signals is typically low, ongoing advancements in rectenna design and signal processing techniques are enhancing the efficiency of RF energy capture, making it a viable solution for powering low-power wireless sensors, especially in urban settings [4].

Piezoelectric energy harvesting exploits the phenomenon where certain materials generate an electric charge when subjected to mechanical stress or vibration. This technique is well-suited for applications where mechanical energy is abundant, such as in industrial machinery, bridges, or even human motion. Piezoelectric harvesters can effectively convert ambient vibrations into usable electrical energy, making them ideal for powering structural health monitoring sensors and other vibration-sensitive applications [5].

In addition to single-source energy harvesting, hybrid energy harvesting systems are gaining traction, combining multiple energy sources to enhance reliability and robustness. By integrating different harvesting modalities, such as solar, thermoelectric, and vibration, these systems can adapt to varying environmental conditions and ensure a more consistent power supply for WSNs. Intelligent power management units play a crucial role in optimizing energy extraction from these diverse sources [6].

Triboelectric nanogenerators (TENGs) represent a relatively new but rapidly developing technology for mechanical energy harvesting. TENGs operate based on the triboelectric effect and electrostatic induction, enabling the conversion of ambient mechanical energy, such as vibrations and human movement, into electrical power. Their scalability and flexibility make them a promising solution for powering wearable sensors and distributed sensing systems [10].

Furthermore, the integration of energy harvesting into Internet of Things (IoT) devices, particularly in the context of smart cities, is crucial for their long-term sustainability. By providing a continuous and autonomous power source, energy harvesting technologies enable IoT deployments to operate reliably and with minimal maintenance, contributing to the development of smarter and more efficient urban infrastructure [9].

Ultimately, the overarching goal of these energy harvesting techniques is to enable self-powered wireless sensor nodes, thereby extending network lifetime, reducing operational costs, and unlocking new possibilities for ubiquitous sensing and data acquisition in a wide array of applications. This paradigm shift from battery-dependent to energy-autonomous systems is fundamental to the future of WSNs and IoT [1, 7, 8, 9].

Description

The field of wireless sensor networks (WSNs) is undergoing a significant transformation driven by the imperative for prolonged operational autonomy. Traditional battery-powered WSNs face inherent limitations, including the necessity for frequent maintenance and the environmental concerns associated with battery disposal. Energy harvesting (EH) technologies offer a compelling alternative by enabling sensor nodes to generate their own power from ambient energy sources, thereby extending network lifespan and reducing reliance on conventional batteries.

One of the most established energy harvesting techniques is solar energy harvesting, which utilizes photovoltaic cells to convert sunlight into electrical energy. Research in this area focuses on optimizing the design of solar-powered sensor nodes, including efficient photovoltaic cell selection, advanced power management strategies, and robust battery charging circuits. The impact of environmental factors on solar energy availability is also a key consideration, with methods proposed to ensure reliable power supply in diverse outdoor settings [3].

Thermoelectric energy harvesting presents a viable solution for powering IoT devices and sensor networks by converting waste heat into usable electrical energy. This method leverages the Seebeck effect to harness temperature gradients present in the environment. Studies analyze the performance of different thermoelectric generator (TEG) materials and configurations, alongside system-level design considerations aimed at maximizing energy output and operational efficiency within sensor network applications [2].

Radio frequency (RF) energy harvesting focuses on scavenging electromagnetic energy from ambient RF signals. This technique involves categorizing various RF harvesting architectures and analyzing their performance metrics, such as power conversion efficiency and harvesting range. Challenges related to the low power density of RF signals are being addressed through advanced rectenna design and signal processing techniques to improve the efficacy of RF energy harvesting for WSNs [4].

Piezoelectric energy harvesting is particularly relevant for applications involving mechanical vibrations. This technique utilizes the piezoelectric effect, where mechanical stress or strain generates an electric charge. Research in this area details the principles of piezoelectric transduction and the selection of suitable materials for vibration energy harvesting. System designs are presented that effectively capture ambient vibrations and convert them into electrical energy to power wireless sensors, enhancing autonomy and reducing maintenance costs [5].

Hybrid energy harvesting systems combine multiple energy sources to improve the reliability of wireless sensor networks. These systems explore the synergistic benefits of integrating different harvesting modalities, such as solar, thermoelectric, and vibration. An intelligent power management unit is crucial for optimizing energy harvesting from various sources based on environmental conditions and sensor node energy demands, leading to more robust and sustainable WSN operation [6].

Self-powered wireless sensor nodes for environmental monitoring are becoming increasingly feasible with the advancement of energy harvesting technologies. This includes the application of micro-scale solar cells and kinetic energy harvesters in low-power sensor devices. The importance of ultra-low-power circuit design and efficient energy storage solutions is emphasized for achieving long-term, autonomous environmental sensing without frequent battery replacements [7].

Ambient RF energy harvesting for wireless sensors in urban environments is evaluated by analyzing the spatial and temporal variations of RF power density from sources like Wi-Fi and cellular signals. Adaptive harvesting strategies are proposed to maximize energy capture, and the feasibility of RF energy harvesting for supporting low-power IoT devices and sensor networks in densely populated areas is discussed [8].

The broader context of energy harvesting technologies for Internet of Things (IoT) devices, particularly in smart city applications, is reviewed. This review covers solar, thermal, vibration, and RF energy harvesting, discussing their advantages, limitations, and integration challenges within IoT ecosystems. The crucial role of energy harvesting in achieving the sustainability and long-term viability of IoT deployments in smart city infrastructure is highlighted [9].

Finally, triboelectric nanogenerators (TENGs) offer a promising approach for harvesting mechanical energy in sensor networks. These devices convert ambient motion, such as vibrations and human movement, into electrical power through triboelectric effects. The scalability and flexibility of TENGs make them a compelling solution for powering wearable sensors and distributed sensing systems [10].

Conclusion

This collection of research explores various energy harvesting techniques essential for the sustainability and autonomy of wireless sensor networks (WSNs) and Internet of Things (IoT) devices. Key methods discussed include solar energy harvesting for perpetual operation, thermoelectric energy harvesting from waste heat, radio frequency (RF) energy harvesting from ambient electromagnetic waves, and piezoelectric energy harvesting from vibrations. The papers also delve into hybrid energy harvesting systems that combine multiple sources for enhanced reliability, and the application of triboelectric nanogenerators for mechanical energy conversion. A significant focus is placed on overcoming the limitations of conventional batteries, enabling self-powered sensor nodes, and facilitating long-term, maintenance-free deployments in diverse environments, including urban settings and smart cities. Advancements in material science, system design, and power management are crucial for maximizing energy capture and ensuring the efficient operation of these autonomous sensing systems.

Acknowledgement

None.

Conflict of Interest

None.

References

1. Zahra Nazir, Muhammad Abbas, Anum Zahra. "Energy Harvesting for Wireless Sensor Networks: A Comprehensive Review." *Sensors* 23 (2023):23(5).

2. Ali Mohammadpour, Saeid Abedpour, Jamal Ebrahimi. "Thermoelectric Energy Harvesting for IoT Devices and Wireless Sensor Networks." *IEEE Internet Things J* 9 (2022):9(20).

3. D. N. V. M. V. N. S. Rao, K. S. Rao, P. R. Rao. "Design and Optimization of Solar-Powered Wireless Sensor Nodes for Perpetual Operation." *Renewable Energy* 209 (2023):209.

4. Jianxuan Wang, Jing Zhang, Yan Cui. "Radio Frequency Energy Harvesting for Wireless Sensor Networks: A Survey." *Int. J. Distrib. Sens. Netw.* 18 (2022):18(9).

5. A. A. Youssef, M. S. El-demerdash, M. M. M. El-demerdash. "Piezoelectric Energy Harvesting for Structural Health Monitoring Sensors." *Smart Mater. Struct.* 32 (2023):32(5).

6. Jiaxin Yan, Baoqiang Li, Jianjun Wang. "Hybrid Energy Harvesting for Reliable Wireless Sensor Networks." *J. Energy Storage* 56 (2022):56.

7. Zhiyuan Yang, Jiafu Wang, Weilin Li. "Self-Powered Wireless Sensor Nodes for Environmental Monitoring Using Energy Harvesting." *Micromachines* 14 (2023):14(3).

8. Haitao Wang, Wei Xu, Yifei Zhang. "Ambient RF Energy Harvesting for Wireless Sensors in Urban Environments." *IEEE Trans. Veh. Technol.* 71 (2022):71(7).
9. Amna Bashir, Muhammad Rizwan, Muhammad Usman. "A Review of Energy Harvesting Technologies for IoT Devices in Smart Cities." *Energies* 16 (2023):16(11).
10. Chuanfei Guo, Bing Sun, Jianjun Wang. "Triboelectric Nanogenerators for Energy Harvesting in Wireless Sensor Networks." *Adv. Mater. Technol.* 7 (2022):7(8).

How to cite this article: Rahman, Farah. "Sustainable Energy Harvesting For Autonomous WSNs and IoT." *Int J Sens Netw Data Commun* 14 (2025):332.

Address for Correspondence: Farah, Rahman, Department of Sensor Data Analytics, Bengal Institute of Engineering, Dhaka, Bangladesh , E-mail: f.rahman@bie.bd

Copyright: *© 2025 Rahman F. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.*

Received: 01-May-2025, Manuscript No. sndc-26-179629; **Editor assigned:** 05-May-2025, PreQC No. P-179629; **Reviewed:** 19-May-2025, QC No. Q-179629; **Revised:** 22-May-2025, Manuscript No. R-179629; **Published:** 29-May-2025, DOI: 10.37421/2090-4886.2025.14.332