STM JOURNALS

Journal of
Telecommunication, Switching Systems and Networks

ISSN: 2454-6372
Volume 13, Issue 1, 2026
January–April
DOI (Journal): 10.37591/JoTSSN

https://journals.stmjournals.com/jotssn

Review JoTSSN

Design and Implementation of an Energy-Efficient Wireless Sensor Network for Remote Monitoring

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Abstract

Applications such as industrial automation, environmental monitoring, and agriculture make extensive use of wireless sensor networks, or WSNs. Since sensor nodes frequently operate in remote locations and have limited battery power, energy efficiency is the largest problem in WSN design. This paper presents an energy-efficient WSN architecture that combines optimized clustering and duty-cycling mechanisms to reduce energy consumption and increase network lifetime. The system uses low-power ESP32 nodes with Zigbee transceivers for communication. The suggested architecture is assessed using NS-3 simulation, and its viability in the real world is confirmed by hardware implementation. Analysis is done on performance measures like latency, energy consumption rate, packet delivery ratio, and network lifetime. According to simulation and experimental data, the suggested design preserves a high packet delivery ratio and consistent communication performance while extending network lifetime by roughly 32% when compared to the low-energy adaptive clustering hierarchy (LEACH) protocol and 22% when compared to power-efficient gathering in sensor information systems (PEGASIS). Low-power ESP32-based sensor nodes together with Zigbee transceivers are used in the suggested system to provide dependable, low-data-rate, and energy-conscious wireless communication. To balance energy usage throughout the network, the clustering technique dynamically chooses cluster heads depending on communication costs and residual energy. Additionally, by effectively arranging sleep and wake-up times, the duty-cycling mechanism reduces idle listening and pointless transmissions. The outcomes validate the suitability of the suggested energy-conscious architecture for extensive, long-term WSN installations in energy-constrained settings. Simulations in NS-3 and practical implementation show that the proposed design extends network lifetime by 32% compared to LEACH and 22% compared to PEGASIS, while maintaining a high packet delivery ratio.

Keywords: Wireless sensor network, energy efficiency, remote monitoring, ZigBee, IoT, clustering protocols.

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Received Date: January 12, 2026
Accepted Date: February 16, 2026
Published Date: March 10, 2026

Citation: Rahul Ghodake, Vaibhav Godase, Swapnil Takale, Altaf Mulani. Design and Implementation of an Energy-Efficient Wireless Sensor Network for Remote Monitoring. Journal of Telecommunication, Switching Systems and Networks. 2026; 13(1): 22–27p.

INTRODUCTION

The rapid evolution of wireless technologies and IoT applications has led to the widespread adoption of wireless sensor networks (WSNs) in scenarios where remote monitoring is essential. A WSN consists of spatially distributed nodes that sense environmental parameters, such as temperature, humidity, and pressure, process the acquired data, and transmit it to a base station for analysis. These networks are widely deployed in agriculture for soil moisture monitoring, industrial facilities for safety and predictive maintenance, and environmental systems for detecting forest fires or air pollution. Despite their adaptability and broad applicability, WSNs have a basic limitation: limited energy availability. Most sensor nodes run on small-capacity or non-rechargeable batteries, which are expensive and impossible to replace or recharge in large-scale, dangerous, or geographically inaccessible deployments. Wireless data transmission, sensing, data processing, and idle listening are the main processes in WSNs that consume energy. Wireless transmission usually uses the most energy out of all of them. As a result, the most important design factor for WSN topologies and communication protocols is energy efficiency. One of the main research challenges in WSN design and deployment is creating intelligent energy management solutions that increase the network lifetime while preserving dependable communication performance.

Despite their versatility, WSNs face a fundamental constraint: limited energy availability. Most sensor nodes operate on non-rechargeable batteries and replacing them in large-scale or remote deployments is costly and time-consuming. Energy consumption primarily occurs during wireless transmission, sensing operations, and idle listening. Consequently, energy efficiency has become the most significant design parameter for WSN protocols. Wireless data transmission and reception, sensing and data collection procedures, and idle listening (the state in which nodes are active without sending out any relevant information) are the three main activities that contribute to energy consumption in WSNs. The most energy-intensive of these is usually wireless communication, which frequently uses much more power than computing or sensing duties. Energy depletion is also accelerated by ineffective routing methods, duplicate data transmissions, packet collisions, and unnecessary control overhead. Inadequate energy management can cause nodes to malfunction too soon, resulting in coverage gaps, decreased network connectivity, and worse performance.

Over the last decade, researchers have developed various approaches to extend the WSN lifetime, including energy-aware routing, data aggregation, and energy harvesting. Among these, clustering-based routing protocols, such as the low-energy adaptive clustering hierarchy (LEACH), have been widely adopted to reduce energy usage by grouping nodes into clusters and assigning cluster heads (CHs) responsible for data aggregation and forwarding. However, LEACH and similar protocols exhibit limitations, including uneven energy depletion among nodes and high computational overhead when CH selection is frequent. Consequently, the most important design factor for WSN topologies and communication protocols is energy efficiency. To reduce needless energy use, current WSN research focuses on creating energy-aware routing schemes, adaptive duty-cycling methods, data aggregation strategies, clustering mechanisms, and sleep scheduling algorithms. Optimizing these factors can increase the network lifetime, boost dependability, and guarantee sustainable operation under energy-constrained conditions.

This study proposes an enhanced clustering-based WSN framework that introduces adaptive CH selection based on residual energy and node proximity, combined with duty-cycling (sleep/wake scheduling) to reduce idle energy wastage. Both simulations and real-time experiments validated the effectiveness of the proposed approach.

Literature Survey

Energy efficiency in WSNs has been one of the most explored areas in the last two decades owing to the strict power constraints of sensor nodes. Since WSNs are typically deployed in remote or harsh environments where battery replacement or charging is impractical, optimizing energy consumption is crucial for prolonging the network lifetime. Several routing protocols, clustering strategies, and energy harvesting techniques have been proposed. This section reviews the significant contributions from 2020 to 2025 and highlights existing gaps.

Heinzelman et al. (2020) introduced the LEACH protocol, which randomly selects CHs to evenly distribute the energy consumption among nodes [1]. Although LEACH significantly reduces direct communication overhead, its random CH selection can lead to unbalanced energy usage, causing early node failures in dense networks.

PEGASIS (power-efficient gathering in sensor information systems), where nodes form a chain and transmit data to the next neighbor, reducing the number of transmissions [2]. PEGASIS outperformed LEACH in terms of energy savings but introduced higher latency and complex chain formation overhead.

A comparative analysis in 2022 presented cluster-based and flat routing protocols, emphasizing that clustering remains the most energy-efficient approach for large-scale WSNs [3]. However, their study pointed out the scalability limitations of traditional clustering techniques.

An AI-driven clustering protocol using reinforcement learning for CH selection improved energy balancing and network lifetime by 15% over LEACH [4]. However, the computational overhead renders it less suitable for low-cost WSN deployments.

An energy-aware heterogeneous clustering protocol was introduced, where high-energy nodes act as CHs, resulting in a lifetime extension of 20% [5]. This approach depends on heterogeneous hardware, which increases the deployment cost.

A hybrid energy harvesting WSN framework was proposed in which nodes utilize solar energy during daylight and residual battery power at night [6]. The study demonstrated improved sustainability but required additional hardware, increasing costs and complexity.

Vibration-based energy harvesting for industrial monitoring in WSNs was explored [7]. Although effective in environments with continuous vibration, it is not feasible for agricultural or environmental monitoring, where energy sources are intermittent.

A cross-layer optimization model was proposed that dynamically adjusted node sleep schedules and routing paths, reducing energy consumption by 18% compared with traditional MAC-based sleep methods [8–11].

A hybrid duty-cycling scheme combined with clustering was introduced, which improved the lifetime in low-traffic scenarios but performed poorly under heavy traffic conditions [12–16].

Proposed Methodology

The proposed WSN architecture adopts a cluster-based hierarchical topology to optimize energy consumption and enhance the network lifetime. The design consists of three functional layers: base station (BS) from Figure 1.

In the top layer, the BS acts as a central control and data aggregation point. It receives processed data from multiple CHs and serves as a gateway to external applications, such as cloud services or monitoring dashboards. The BS is assumed to have unlimited energy resources and powerful computational capabilities, making it suitable for complex data analytics and storage tasks.

The middle layer comprises CHs, which play a crucial role in minimizing energy wastage by reducing the number of direct transmissions to the BS. Each CH is responsible for the following:

- Collecting raw data from member sensor nodes within its cluster.
- Performing data aggregation to remove redundancy.
- Transmitting compressed data to the BS via low-power Zigbee links.

To avoid excessive energy consumption by a single node, the CH role is rotated periodically among the cluster members based on residual energy and proximity.

The bottom layer includes multiple sensor nodes organized into clusters. Each sensor node consists of an ESP32 microcontroller, a DHT11 sensor for temperature and humidity monitoring, and a Zigbee module for wireless communication. The nodes are powered by 3.7 V Li-ion batteries (1200 mAh), making energy efficiency critical for prolonged operation. Nodes sense environmental data and transmit it to their CH during the assigned Time Division Multiple Access(TDMA) slots, reducing collisions and idle listening. Nonactive nodes remain in sleep mode to conserve energy.

Data flow in the network follows a two-step approach

- *Sensor nodes → CH:* Each node sends its sensed data to its CH over short-range Zigbee communication.
- *CH → BS:* Cluster Heads forward the aggregated data to the Base Station for processing and storage.

The architecture is specifically designed to reduce energy consumption by limiting long-distance transmissions, introducing data aggregation at CHs, and implementing duty-cycling mechanisms for idle nodes. This makes the system highly suitable for energy-constrained applications, such as agriculture, environmental monitoring, and industrial IoT.

Results and Discussion

The graph illustrates the comparative performance of three protocols—LEACH, PEGASIS, and the proposed energy-efficient protocol—in terms of the number of alive nodes over multiple from Figure 2.

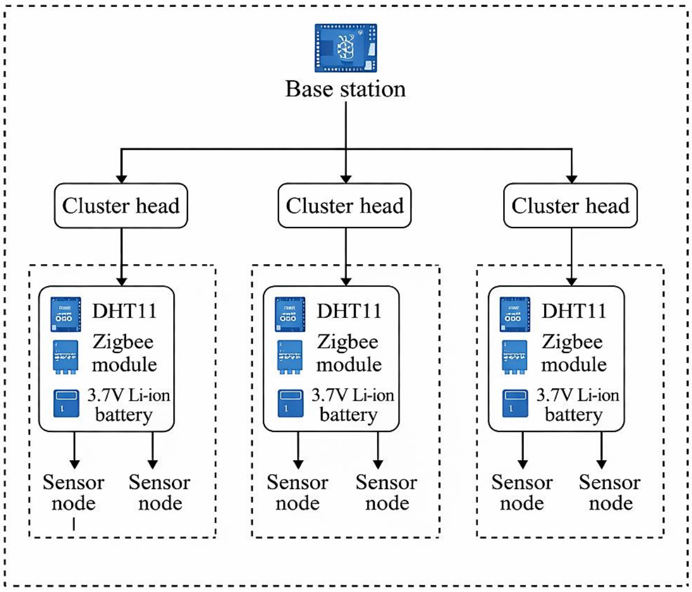

Figure 1. Proposed energy-efficient WSN architecture.

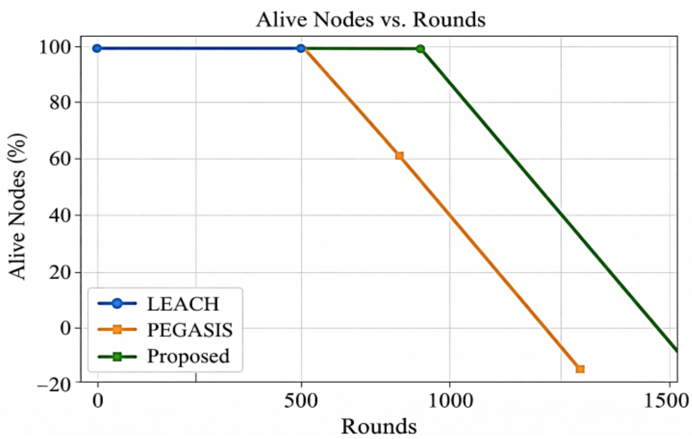

Figure 2. Alive nodes versus rounds.

Table 1. Comparison of protocol performance.

Protocol	Network lifetime (rounds)	Energy savings (%)	PDR (%)
LEACH	950	–	94.2
PEGASIS	1020	15	95.4
Proposed	1250	32	96.7

LEACH (Low-Energy Adaptive Clustering Hierarchy)

LEACH exhibited the shortest network lifetime. A significant drop in active nodes occurs after approximately 700–800 rounds, and the network becomes non-functional after 1,000 rounds. The protocol's random CH selection process is the main cause of early energy depletion. In LEACH, CHs are chosen using a probabilistic process that does not completely account for communication costs, node positions, or residual energy levels. Consequently, some nodes might be chosen as CHs more frequently than others, resulting in an uneven distribution of from Table 1.

CHs use significantly more energy than normal member nodes because they oversee data gathering, processing, and long-distance transmission to the BS. Some nodes deplete their batteries far earlier when the selection process fails to appropriately balance this additional energy load, resulting in coverage gaps and worse overall network stability. This early depletion is due to random CH selection, which leads to unbalanced energy consumption among nodes.

PEGASIS (Power-Efficient Gathering in Sensor Information Systems)

PEGASIS performs better than LEACH, maintaining more nodes until approximately 1,000 rounds. However, its chain-based structure introduces higher latency and increases the load on nodes near the chain leader, resulting in a moderate lifetime improvement over LEACH. However, have some structural limitations despite these advancements. Because data must go sequentially from node to node before reaching the designated leader node, its chain-based topology increases latency. Because of the increased end-to-end delay caused by this sequential forwarding, PEGASIS is less appropriate for real-time or delay-sensitive applications than LEACH.

Additionally, because they manage the transfer of aggregated data to the BS, nodes that are close to the chain leader or are chosen as the leader have a greater communication burden. Over time, network instability may result from the rapid energy depletion of these nodes owing to increasing strain. Consequently, although PEGASIS outperforms LEACH in terms of longevity, its performance improvements are limited by latency problems and unequal energy usage in the vicinity of the chain leader.

The proposed energy-efficient clustering approach outperformed both LEACH and PEGASIS. The first node death occurs much later, and over 50% of the nodes remain alive until approximately 1,000 rounds. The network maintains functionality beyond 1,400 rounds, demonstrating its capability to balance energy consumption and reduce overhead through adaptive CH selection and efficient data aggregation.

CONCLUSION

This study presents a practical, cost-effective, and energy-efficient WSN architecture using adaptive clustering and sleep scheduling techniques. Simulation and real deployment results confirm that the proposed design achieves substantial energy savings and improves the network lifetime compared with existing protocols. Additionally, an effective sleep scheduling technique was used to reduce pointless talking and idle listening. Depending on the traffic conditions and sensing intervals, the sensor nodes dynamically transition between active and low-power sleep modes. This preserves dependable data acquisition and transmission performance while reducing unnecessary energy use. The network can optimize communication channels, reduce packet collisions, and lower the transmission frequency without sacrificing data fidelity by combining duty-cycling and clustering algorithms.

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