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Optimizing Energy Efficiency in Wireless Sensor Networks: Challenges and Innovative Solutions: A Survey

Arun Panwar[1], Awadhesh Kumar Maurya[2], Rajnish Pandey[3], Rajesh Kumar Singh[4]

[1]Arun Panwar,[2] Awadhesh Kumar Maurya, [3]Rajnish Pandey,
[4]Rajesh Kumar Singh, Department of Information Technology
Institute of Engineering and Technology
Dr. Rammanohar Lohia Avadh University
Ayodhya (U.P.)- India

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Abstract - The ubiquity of Wireless Sensor Networks (WSNs) in modern communication stems from breakthroughs in micro-electronics, enabling the creation of wireless micro-sensors that underpin their functionality. WSNs play a pivotal role in transmitting crucial environmental data to central Base Stations (BS), facilitating applications across diverse sectors such as artificial intelligence, healthcare, military operations, diagnostics, and environmental monitoring, including fire detection. Despite their widespread adoption, WSNs face persistent challenges in sensor node architecture. Random deployment strategies often result in coverage overlaps, communication inefficiencies, and suboptimal resource utilization, compounded by issues like low battery power and limited transmission capacity. These challenges necessitate the reduction of packet sizes to conserve energy and improve network efficiency. Moreover, the placement of sensor nodes in remote or inaccessible locations adds complexity to maintenance tasks, impacting network longevity and reliability. Addressing these challenges is imperative for sustaining efficient WSN operation and optimizing energy usage, driving the need for innovative protocols and energy-efficient strategies to enhance performance and ensure long-term viability across various WSN applications.

***Key Words*:** WSN, protocols, sensor, Networks

1.INTRODUCTION

Wireless sensor networks have become essential for communication in the twenty-first century. Micro-electronics breakthroughs have made it easier to create wireless micro-sensors, which are the foundation of WSNs [1]. These networks play a crucial role in transmitting environmental data to a central Base Station (BS). These networks' nodes, which are placed either haphazardly or purposefully throughout various areas, are used for a variety of purposes such as artificial intelligence, healthcare, military operations, clinical diagnostics, and the detection of forest fires [2][3].

1. Functional Block Diagram of a Wireless Sensor Node

The functional block diagram of a multifunctional wireless sensor node is shown in Figure 1. Flash memory is used by remote nodes to store data that is received from a base station or in response to events that are detected. The embedded firmware has the capacity to update the network wirelessly, which increases the node's capability and adaptability [6][7].

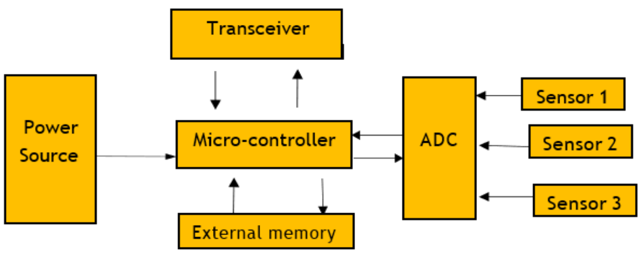

Fig -1: Figure

Several international research projects have been devoted to developing protocols and techniques to reduce sensor network energy usage as a whole. A sensor network's lifespan may be significantly increased by coordinating protocols and algorithms with the underlying hardware and design, which would allow nodes to effectively reduce their energy usage [9][10].

2. LITERATURE REVIEW

In [11], the study conducted by researchers introduced a fuzzy continuous node refining approach targeting the enhancement of multi-layer routing efficiency within Wireless Sensor Networks (WSNs). With a clear focus on fortifying message security and augmenting sensor node tracking capabilities, this method represents a significant advancement in the realm of WSN optimization. By employing fuzzy logic, the researchers aimed to refine the node selection process, thereby streamlining routing operations and improving overall network performance.

In [12], Energy Adaptive Distributed based Energy-Efficient Clustering (EADEEC) method is proposed, presenting a novel approach that places resilience and the intrinsic value of device nodes at the forefront. Recognizing the critical role played by cluster heads in WSNs, the authors leveraged the Improved-DEEC approach to meticulously optimize cluster head selection. By carefully balancing energy consumption and distribution across the network, EADEEC holds the promise of extending the operational lifespan of WSNs while simultaneously enhancing their efficiency and reliability.

In [13], researchers embarked on a journey to devise an ensemble approach aimed at enhancing the Low Energy Adaptive Clustering Hierarchy (LEACH) algorithm. With the overarching objective of minimizing energy destroy and promoting even energy circulation across all nodes within the network, this endeavor represents a significant step forward in the pursuit of energy efficiency within WSNs. By harnessing the power of ensemble techniques, the researchers sought to capitalize on the strengths of multiple algorithms, thereby creating a synergistic solution that addresses the inherent complexities of WSNs while paving the way for sustainable and resilient network operation.

In [14], introduced a novel distributed protocol featuring of a cluster structure and rendezvous SNs to enable energy-efficient and long-lasting process. This protocol dynamically adjusts cluster dimensions and controls CH proximity to the Mobile Sink (MS) path.

In [15], a power-efficient, tree-like cluster header structure for heavily distributed WSN IoT devices was presented by the authors.

In [16], researchers introduced a hybrid energy efficient clustering (HEEC) protocol, which represents a novel approach by blending distributed and centralized ways across multiple layers within Wireless Sensor Networks (WSNs). This innovative method seeks to optimize energy consumption by utilizing multi-stage data routing for efficient data transmission. By combining the strengths of both centralized and distributed approaches, HEEC aims to achieve improved energy efficiency and prolong the operational lifespan of sensor networks. The integration of Wireless Sensor Networks (WSNs) into data analysis systems is the main issue at hand, with an emphasis on improving energy efficiency. Even though WSNs have a great deal of potential for providing real-time data monitoring and analysis, managing energy usage can be difficult when implementing them. In this scenario, WSN nodes' energy and bandwidth constraints become crucial variables in energy efficiency optimization. To minimize energy consumption and maximize network resource usage, data transmission and routing methods must be managed effectively.

Author Paper Number	Methodology	Advantages
[11]	Fuzzy-based continuous node refining	Enhances multilayer routing efficiency, fortifies message security, improves sensor node tracking capabilities
[12]	Energy Adaptive Distributed Energy-Efficient Clustering	Extends operational lifespan, enhances efficiency and reliability, optimizes cluster head selection
[13]	Ensemble based technique to enhance LEACH protocol	Minimizes energy ruin, promotes equal energy distribution, creates a synergistic solution for sustainable and resilient network operation
[14]	Distributed protocol with cluster structure and rendezvous nodes (RNs)	Enables energy efficient working, dynamically adjusts cluster dimensions, influences CH closeness to the Mobile Sink path
[15]	Tree-like cluster header-oriented framework	Energy-efficient framework for heavily allotted WSN IoT devices
[16]	PR-LEACH based routing	Addresses power optimization challenges in IoT enabled networks, minimizes energy consumption, improves communication effectiveness
[17]	Route-planning system for Software-Defined Vehicular Networks (SDVNs)	Optimizes route selection, enhances traffic management and safety, optimizes resource utilization
[18]	LEACH-SF based routing	Establishes balanced clusters, prolongs network lifetime, optimizes cluster formation and data transmission, enhances network stability and sustainability
[19]	Least number of sensor nodes for active detection and QoS estimation	Provides insights into sensor network deployment, scalability, and performance considerations
[20]	Mobile sinks for energy-efficient sensor network operation	Conserves node energy, extends operational lifespan, proactive cluster head selection, sustainable network operation

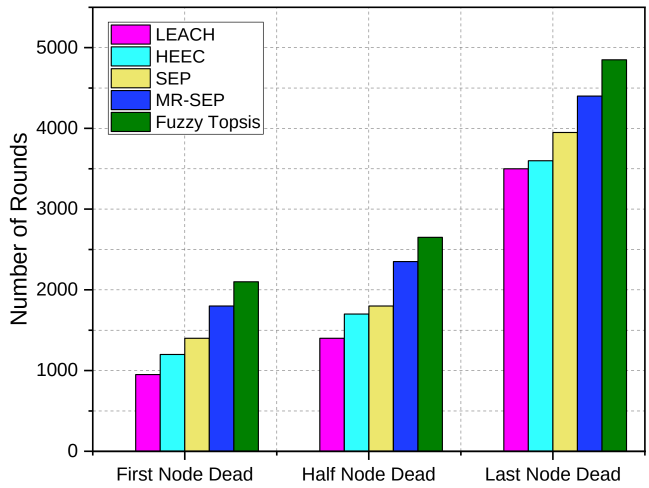

Figure 2: Different protocols at different time intervals

In WSNs, the stages of "First Node Dead," "Half Node Dead," and "Last Node Dead" are crucial in node energy depletion or failure. "First Node Dead" denotes the first node failure, indicating potential concerns with energy management tactics or node location. As nodes advance to "Half Node Dead," around half of the network's nodes deplete or fail, resulting in poor performance and data dependability. Finally, "Last Node Dead" indicates full network failure when the final node depletes its energy, emphasizing the significance of energy-efficient protocols and effective fault tolerance mechanisms in WSN deployments to maintain network functioning and data integrity. Hybrid approach such as MR-SEP and Fuzzy Topsis showed more number of rounds survival of network at different time intervals as shown in figure2.

3. CONCLUSIONS AND FUTURE WORK

The examination of node energy depletion phases in Wireless Sensor Networks (WSNs), which include "First Node Dead," "Half Node Dead," and "Last Node Dead," highlights the need of energy management systems and fault tolerance mechanisms. The escalation from early node failures to network-wide outages emphasizes the importance of reliable energy-efficient protocols and fault-tolerant architectures in WSN deployments. Future research should concentrate on improving hybrid techniques like as MR-SEP and Fuzzy Topsis, which show improved network survivability over a variety of time periods. Furthermore, advances in energy harvesting technologies and adaptive routing algorithms show promise for extending WSN operating lifespans and maintaining data integrity in dynamic environmental monitoring situations.

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