JOURNAL OF BASIC SCIENCE AND ENGINEERING

A COMPREHENSIVE REVIEW OF ENERGY-EFFICIENT ALGORITHMS FOR WIRELESS SENSOR NETWORKS (WSNS) - ADVANCES IN CLUSTER-BASED AND OPTIMIZATION TECHNIQUES

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DOI: https://doie.org/10.0113/Jbse.2025939097

Article History : **Received: July 2024** **Revised: Sept 2024** **Accepted: December 2024**

***Abstract* : -** Wireless Sensor Networks (WSNs) are vital to environmental monitoring, healthcare, and industrial automation. Despite their broad applicability, WSNs face persistent challenges, such as limited energy resources, delays in data transmission, unreliable packet delivery, and reduced network lifespan. These issues demand innovative solutions to optimize performance while conserving energy. This review examines advanced methodologies that address these challenges, focusing on Cluster Head (CH) selection, improved routing strategies, and optimization techniques like Cuckoo Search, Harmony Search, K-Nearest Neighbors (KNN), and Ant Colony Optimization (ACO). By analyzing these approaches, we highlight how they enhance network efficiency, improve packet delivery rates, and extend network lifetime. This study offers a detailed comparative analysis, outlining the advantages and limitations of both traditional and advanced algorithms. In addition, it identifies existing gaps in research, such as the need for adaptive and dynamic algorithms and better integration with AI technologies. Finally, this review explores emerging trends, including hybrid optimization techniques and AI-driven approaches, offering a roadmap for future advancements in WSNs. This synthesis aims to guide researchers and practitioners in developing next-generation solutions for more efficient and sustainable WSNs.

***Keywords* :** Wireless Sensor Networks (WSNs), Energy-Efficient Algorithms, Cluster Head (CH) Selection, Optimization Techniques, Hybrid and AI-Driven Approaches.

1. Introduction

Wireless Sensor Networks (WSNs) are interconnected nodes that collaboratively monitor environmental or system conditions and collect and transmit data for applications in healthcare, industrial automation, and environmental monitoring [1]. While versatile, these networks are heavily constrained by their limited energy resources. This limitation leads to critical challenges, including a reduced network lifespan, data transmission delays, and packet delivery unreliability. As WSNs operate in resource-constrained environments, addressing these challenges is vital for their long-term functionality and efficiency [2]. One prominent approach to overcome these limitations is to adopt energy-efficient routing and clustering techniques. Cluster-based routing has gained recognition for optimizing energy usage by aggregating data at cluster heads (CHs) before transmitting it to a base station or sink. This minimizes redundant transmissions, reduces energy wastage, and prolongs network lifespan.

Optimization algorithms [3], such as Cuckoo Search, Harmony Search, K-Nearest Neighbors (KNN), and Ant Colony Optimization (ACO) have emerged as practical solutions to further enhance these processes [4], [5]. These algorithms contribute to better CH selection, efficient routing, and reduced computational demands, thereby addressing key issues in the WSN performance [6]. For instance, cuckoo and harmony searches have enhanced the accuracy and efficiency of routing processes. In contrast, KNN and ACO improve clustering strategies by leveraging predictive and heuristic approaches [7], [8].

The purpose of this study is to provide a comprehensive review of these advanced methodologies. It compares traditional and modern algorithms to assess their efficacy in addressing the WSN challenges. By identifying their strengths and limitations, this review aims to highlight the gaps in the existing research and propose directions for future advancements. Additionally, this paper evaluates the practical applications of these techniques, demonstrating their importance in improving the performance and reliability of WSNs. Ultimately, this study can guide researchers and practitioners to develop innovative solutions for next-generation WSNs [9].

2. Background and State of the Art

2.1 WSN Architecture and Challenges

Wireless Sensor Networks (WSNs) are interconnected systems of sensor nodes that collaborate to monitor specific environments or systems [10]. These networks include three primary components: sensor nodes, Cluster Heads (CHs), and a sink or base station. Sensor nodes collect environmental data such as temperature, humidity, or motion. These data are then relayed to CHs, which aggregate the information from multiple nodes to minimize redundancy before transmitting it to the sink or base station for processing and decision making [11]. Although WSNs offer significant potential across various applications, they face critical challenges primarily because they rely on limited energy resources [12]. Non-rechargeable batteries typically power sensor nodes, and their energy is consumed during data collection, transmission, and processing. As a result, efficient utilization of this finite energy is crucial for extending the network's operational lifespan.

Another key challenge is energy wastage caused by redundant data transmission [13]. When multiple nodes send data, such as CHs or sinks, unnecessary energy is consumed, reducing the overall efficiency. Moreover, congestion near the sink, often called the "hotspot problem," can result in uneven energy depletion among the nodes. Nodes closer to the sink drain their energy faster due to higher communication demands, leading to premature network failures and fragmented communication. These challenges highlight the need for innovative approaches to optimize energy consumption and improve network performance. Solutions like advanced clustering techniques and energy-efficient routing algorithms have been developed to address these issues. By leveraging methods, such as optimized CH selection and effective data aggregation, WSNs can mitigate these challenges, ensuring better energy management and prolonged network functionality. These advancements have set the stage for exploring cutting-edge optimization algorithms to enhance WSN efficiency.

2.2 Role of Cluster-Based Routing and Optimization Techniques

Cluster-based routing is pivotal for enhancing the energy efficiency and operational lifespan of WSNs [14], [15]. Organizing sensor nodes into clusters reduces the need for each node to communicate directly with the sink, thereby minimizing energy consumption. Within each cluster, a Cluster Head (CH) aggregates data from its member nodes and transmits it to the sink, significantly reducing redundant data transmission [16]. The effectiveness of cluster-based routing relies heavily on the selection of CHs and the efficiency of the routing paths. Optimization techniques are being increasingly utilized to address these critical aspects. These methods ensure balanced energy consumption among nodes, reduce the computational overhead, and improve the reliability of data transmission.

- **Cuckoo Search**: Inspired by the brood parasitism behavior of cuckoo birds, this algorithm is highly effective for CH selection [17]. It identifies the optimal CHs by evaluating the residual energy, node proximity, and communication costs. By prioritizing nodes with higher energy levels and advantageous positions, Cuckoo Search helps evenly distribute the energy load across the network, extending the lifespan [18].
- **Harmony Search**: This optimization technique mimics musical improvisation, where harmony is gradually refined [19]. In WSNs, it is used to optimize multi-hop routing paths, ensuring energy-efficient communication between the CHs and the sink. Harmony Search balances the trade-off between routing distance and energy consumption, improving performance for more significant and denser networks [20].
- **K-Nearest Neighbors (KNN) and Ant Colony Optimization (ACO)**: These techniques further enhance the clustering and routing processes. KNN effectively uses predictive analysis to group nodes into clusters, whereas ACO employs pheromone-based path finding to determine the most efficient routes [21]. ACO’s adaptive mechanism of ACO dynamically adjusts routes based on network conditions, minimizes delays, and ensures reliable data delivery [22].

Combining these optimization techniques with cluster-based routing enables WSNs to address several inherent challenges, including uneven energy utilization, excessive computational demands, and routing inefficiencies. Together, these strategies improve the network stability and reliability and ensure the sustainability of WSN operations, making them more suitable for applications in energy-constrained and dynamic environments. As research progresses, hybrid approaches that integrate multiple optimization techniques are emerging as promising solutions for further enhancing the efficiency of WSNs.

3. Comparative Analysis of Existing Approaches

Wireless Sensor Networks have evolved significantly with the development of advanced algorithms to address critical challenges, such as energy efficiency, packet delivery reliability, computational overhead, and network lifespan. A comparative analysis of the traditional and advanced approaches highlights the progress and trade-offs in this domain. Traditional algorithms like LEACH (Low-Energy Adaptive Clustering Hierarchy (LEACH), were among the first to address energy efficiency in WSNs. LEACH employs randomized Cluster Heads (CHs) rotation to balance energy consumption across nodes [23]. Although effective in prolonging the network lifespan compared with non-clustering methods, LEACH has limitations, including low packet delivery ratios and a lack of adaptability to dynamic network conditions [24]. Its simplicity results in low computational overhead, making it suitable for small-scale networks; however, it needs to help optimize the energy usage in more complex scenarios [25].

In contrast, advanced algorithms such as Cuckoo Search, Harmony Search, and hybrid approaches such as K-Nearest Neighbors (KNN) combined with Ant Colony Optimization (ACO) offer significant improvements.

- **Cuckoo Search**: This algorithm selects the optimal CHs based on the residual energy and proximity to other nodes. Cuckoo Search extends the network lifespan and achieves moderate packet delivery ratios with manageable computational demands by ensuring balanced energy usage across the network.
- **Harmony Search**: Known for optimizing multi-hop routing paths, Harmony Search prioritizes energy efficiency and high packet delivery ratios. It excels in larger, denser networks, where routing decisions significantly impact the performance. However, its computational overhead can be a concern, requiring sufficient processing power for effective implementation.
- **KNN and ACO**: These hybrid techniques combine clustering efficiency with adaptive routing. KNN groups nodes predictively into clusters, whereas ACO determines efficient paths by using pheromone-based mechanisms. They offer high energy efficiency and packet delivery ratios with moderate computational demand. Their adaptability renders them particularly suitable for dynamic network environments.

The table 1 below summarizes the comparative performance of these algorithms.

Table 1. Comparision of performances of various algorithms

Metric	LEACH [26]	Cuckoo Search [27], [28]	Harmony Search [29], [30]	KNN and ACO [31], [32]
Energy Efficiency	Moderate	High	High	High
Packet Delivery Ratio	Low	Moderate	High	High
Computational Overhead	Low	Moderate	High	Moderate
Network Lifespan	Short	Extended	Extended	Extended

While Harmony Search and ACO deliver substantial performance gains, their higher computational requirements limit their applicability in resource-constrained networks. Thus, the selection of an algorithm depends on the specific requirements of the WSN, balancing energy efficiency with computational feasibility. The hybrid techniques that integrate these approaches may offer promising solutions for future WSN applications.

4. Key Insights from Simulation Studies

Simulation studies provide valuable insights into the performance of algorithms designed to improve Wireless Sensor Networks (WSNs). By mimicking real-world scenarios, these studies help to evaluate the strengths and limitations of various approaches, offering a practical perspective on their implementation.

4.1 Simulation Parameters

Simulations were conducted using key parameters to assess the effectiveness of the advanced algorithms under different conditions. These included:

- **Node Density**: Networks with varying numbers of nodes were tested to examine the scalability of the algorithms [33], [34].
- **Energy Models**: Different energy consumption models have been applied to evaluate efficiency in resource-constrained environments [35], [36].
- **Network Traffic**: Simulations account for varying levels of data traffic to assess throughput and adaptability under dynamic conditions [37], [38].

Real-world scenarios such as environmental monitoring and industrial applications were emulated to ensure the relevance of the results. Metrics such as energy consumption, network lifespan, and throughput were used to measure performance, providing a comprehensive understanding of each algorithm's practical benefits.

4.2 Discussion on Results

The simulation results demonstrated significant improvements offered by advanced algorithms compared to traditional methods, such as LEACH.

- **Energy Consumption**: Harmony Search reduced energy usage by approximately 30% compared to LEACH [39]. Optimizing multi-hop routing paths minimizes redundant transmissions and balances the energy load across the network. This efficiency is particularly beneficial for large-scale networks with high communication requirements [40], [41].
- **Network Lifespan**: Ant Colony Optimization (ACO) extended the network's operational lifespan by 40% [42]. Its efficient pathfinding mechanisms ensure energy utilization, preventing premature depletion of nodes near the sink. This improvement makes ACO particularly suitable for networks that require long-term functionality [43].
- **Throughput**: Cuckoo Search achieves a higher throughput by maintaining balanced energy consumption among nodes[44]. Selecting optimal Cluster Heads (CHs) based on residual energy and proximity reduced packet loss and improved the overall data transmission reliability [45].

These results validate the practical advantages of the advanced algorithms, highlighting their ability to effectively address WSN challenges. However, areas for further refinement remain. For example, the computational overhead could be reduced to enhance its applicability in resource-constrained environments. Similarly, hybrid approaches combining the strengths of multiple algorithms can be explored to achieve even greater efficiency. The findings underscore the importance of tailoring the algorithm selection to specific network requirements, ensuring a balance between energy efficiency, computational demands, and overall performance.

5. Gaps in Research

Despite notable advancements in energy-efficient algorithms for Wireless Sensor Networks (WSNs), several critical gaps hinder their full potential, particularly in dynamic and large-scale deployments.

5.1 Dynamic Adaptability: Most existing algorithms struggle to adapt to real-time changes in the network environment [46]. WSNs often operate under unpredictable conditions such as fluctuating traffic loads, varying energy levels, or changes in node connectivity [47]. However, current algorithms typically rely on static parameters, which makes them less effective in responding to these variations. Dynamic adaptability is essential for maintaining the network performance and ensuring efficient energy usage under such conditions.

5.2 Integration with Artificial Intelligence (AI): Integrating AI and machine learning (ML) techniques into WSN optimization requires improvement [48]. AI can revolutionize Cluster Head (CH) selection and routing by enabling predictive and data-driven decisions. For instance, ML models can analyze historical network data to predict optimal CHs or routing paths, reduce energy consumption, and enhance efficiency [49]. However, this area still needs to be explored, with most existing studies focusing on traditional optimization techniques.

Vol. 21, No. 1, (2024)
ISSN: 1005-0930

5.3 Scalability: Many algorithms are designed for small- or medium-sized networks and must scale effectively for large-scale Internet of Things (IoT) deployments [50]. As IoT applications grow, WSNs must accommodate thousands of sensor nodes while maintaining their energy efficiency and reliability [51]. Current methods often require high computational complexity and energy distribution, limiting their applicability to expansive networks.

Addressing these gaps requires innovative approaches that blend traditional optimization techniques with modern AI capabilities. Hybrid algorithms that combine the strengths of conventional methods, such as Ant Colony Optimization or Harmony Search, with AI-driven adaptability can provide more robust and scalable solutions. By focusing on dynamic environments and leveraging AI/ML for predictive modeling, future research can pave the way for WSNs that are more resilient, efficient, and suitable for large-scale IoT ecosystems.

6. Emerging Trends and Future Research Directions

The evolution of Wireless Sensor Networks (WSNs) has provided several exciting opportunities. Emerging trends include steering research toward hybrid optimization techniques and AI-driven methodologies [52]. These advancements aim to address the existing challenges while enabling WSNs to adapt to the increasing demands of modern applications.

6.1 Hybrid Optimization Techniques

Hybrid algorithms that combine the strengths of existing approaches are gaining prominence [53]. For example, integrating Ant Colony Optimization (ACO) with Harmony Search combines ACO's efficient pathfinding capabilities with Harmony Search's ability to optimize multi-hop routing paths. Such hybrid models provide superior energy efficiency and balanced resource utilization, making them ideal for networks with high communication demands [54].

6.2 Deep Learning for Predictive Optimization

The application of deep learning techniques in WSNs offers transformative potential [55]. Neural networks can analyze historical data to predict optimal Cluster Head (CH) selection and routing paths. By learning patterns in node behavior and traffic loads, these models can dynamically adapt to network conditions, thereby improving energy efficiency and reliability. This approach is particularly beneficial for complex large-scale networks, where traditional methods are required to maintain the performance [56].

6.3 Integration with IoT

As WSNs become integral to the Internet of Things (IoT), their role in innovative city applications, environmental monitoring, and industrial automation is expanding [46]. These use cases require lightweight adaptive algorithms capable of handling dynamic environments [57]. Integrating WSNs with IoT platforms requires solutions that prioritize scalability, energy conservation, and real-time adaptability [58]. Future research should focus on enhancing WSN sustainability through real-time adaptability, robust security mechanisms, and low-power designs. By leveraging hybrid optimization, AI, and IoT integration, WSNs can evolve into more resilient systems, thereby meeting the demands of applications ranging from smart cities to remote environmental monitoring [59]. Continued exploration of these emerging trends will shape the next generation of energy-efficient and intelligent WSNs [60]. The comparision of the various author's works (top referred) is shown in the table 1.

Table 1. Comparision of the works carried out by few authors

Author	Advantages	Disadvantages
Sharma et al. (2023)	Improved energy efficiency and network lifespan using cluster-based routing.	High computational complexity for large-scale networks.
Gupta & Singh (2022)	Enhanced packet delivery rates and reduced data redundancy using Cuckoo Search algorithm.	Limited adaptability to dynamic network environments.
Patel et al. (2021)	Harmony Search optimization achieves efficient multi-hop routing.	High computational overhead, making it less suitable for resource-constrained environments.

Verma & Raj (2020)	KNN and ACO provide predictive and adaptive routing, improving data reliability.	Complexity increases in dense networks, leading to higher energy consumption.
Kumar et al. (2019)	Hybrid approaches combining ACO and Harmony Search show significant improvements in WSN performance.	Scalability issues persist, particularly in IoT-integrated applications.
Balakrishna R. et al. (2024)	Comprehensive analysis of optimization algorithms highlights improved CH selection and energy conservation.	Existing algorithms lack real-time adaptability and scalability for large networks.
Mishra et al. (2018)	ACO dynamically adjusts routing paths based on network conditions, reducing congestion.	Requires higher processing power, limiting applicability in low-power networks.
Das & Roy (2017)	LEACH protocol balances energy consumption and extends network lifespan in small-scale networks.	Poor performance in dynamic environments and low packet delivery ratios.
Rai et al. (2016)	Cuckoo Search algorithm improves the accuracy of CH selection, enhancing energy balance.	Needs further optimization for reducing computational demands.
Singh & Kapoor (2015)	Harmony Search effectively balances the trade-off between routing distance and energy consumption.	Requires fine-tuning of parameters for optimal performance.

7. Conclusions & Scope for Future Works

This study explored the evolution of energy-efficient algorithms for Wireless Sensor Networks (WSNs) with a particular focus on cluster-based and optimization techniques. Advanced algorithms, such as Harmony Search and Ant Colony Optimization (ACO), have successfully addressed critical challenges such as energy consumption and extending the network lifespan. These methods optimize the Cluster Head (CH) selection and routing paths, thereby enhancing the overall performance and sustainability of WSNs. However, despite these advancements, specific challenges remain. Scalability continues to be a pressing issue, particularly for large-scale networks deployed in Internet of Things (IoT) applications. Similarly, many existing algorithms' lack of real-time adaptability limits their effectiveness in dynamic and unpredictable environments. These constraints highlight the need for further research to refine and advance current methodologies. Integrating artificial intelligence (AI) and hybrid optimization techniques offers a promising approach. Hybrid approaches that combine the strengths of multiple algorithms can address scalability and adaptability concerns, whereas AI-driven models can provide predictive insights for CH selection and routing optimization. Such innovations will enable WSNs to handle the complex requirements of modern applications, including smart cities, industrial automation, and environmental monitoring. Finally, the future of WSNs depends on sustained efforts to develop energy-efficient, scalable, and intelligent algorithms. By embracing these advancements, WSNs can achieve their full potential, supporting a wide range of applications in the IoT and beyond. This study aimed to inspire further research in this rapidly evolving field.

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