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A COMPREHENSIVE STUDY ON SUSTAINABLE WIRELESS SENSOR NETWORKS: EVALUATING ENERGY-EFFICIENT CLUSTERING APPROACHES

Mr. P. Prabhu
Research Scholar, Park's College (Autonomous), Chinnakarai, Tirupur, Tamilnadu - 641605.
Email:pprabhu3582@gmail.com

Dr. P. Periyasamy
Associate Professor, Department of Computer Science, Park's College (Autonomous), Chinnakarai, Tirupur, Tamilnadu – 641605. Email:pereee@yahoo.com
* corresponding author

Abstract

In Wireless Sensor Networks (WSNs), optimizing data transmission routes is essential for enhancing network longevity, primarily by reducing the total energy expenditure along these routes. To enhance scalability and increase the efficiency of data aggregation, sensor nodes are typically organized into distinct, non-overlapping groups known as clusters. These clusters are essential for establishing hierarchical structures within WSNs, optimizing the use of the limited resources in sensor nodes, and extending the network's lifespan. This paper seeks to present a comprehensive review of the clustering algorithms available in WSN literature, providing an up-to-date analysis of the field. This paper introduces a specialized taxonomy that emphasizes energy-efficient clustering strategies in WSNs. Our primary objective is to systematically categorize and evaluate the various methodologies reported in the literature, focusing particularly on enhancing energy efficiency and promoting sustainable network performance.

1. Introduction

WSNs have become essential technological platforms, showcasing their capability to monitor, collect, and transmit data across diverse applications, ranging from environmental monitoring to industrial processes. However, despite significant progress in this field, one of the major challenges remains the limited energy supply of sensor nodes. Since these nodes often rely on batteries or other portable power sources, there is a critical need for innovative solutions to optimize energy consumption and extend the network's lifespan [1]. In this context, energy-efficient clustering has become a critical strategy for navigating the complex trade-offs between network performance, resource utilization, and energy conservation [2].

The increasing use of WSNs, which consist of many small embedded devices capable of sensing, computing, and communicating, highlights the need for energy-efficient practices. A key factor in this advancement has been the evolution of Micro-Electro-Mechanical System (MEMS) sensor technology, which has enabled the creation of smart sensors—small devices with restricted power, processing, and computing capacities [2-4]. Within WSNs, these smart sensors face constraints in processing power, communication bandwidth, and storage capacity, highlighting the need for careful and energy-efficient resource management.

This review seeks to offer a thorough overview and detailed evaluation of current research focused on energy-efficient clustering techniques in WSNs [5]. Clustering, which involves grouping sensor nodes into clusters, presents a viable approach to achieving network scalability, resource sharing, and optimal energy consumption. However, the review will also address gaps in the current literature, including the limited scope of existing clustering algorithms, which may not encompass the most recent innovations. These algorithms will be evaluated through a comparative analysis using critical performance criteria, including energy efficiency, scalability, and robustness, to highlight the advantages and limitations of each method [5-7].

Additionally, this review will explore the practical implementations of these algorithms in real-world scenarios, supported by case studies to enhance relevance. It will consider the performance of clustering algorithms in dynamic environments characterized by node mobility, varying energy levels, and changing network topologies. The integration of energy harvesting techniques with clustering algorithms will also be examined, as these approaches can significantly enhance the sustainability of WSNs.

Moreover, while focusing on energy efficiency, the review will not overlook the importance of security in WSNs. It will explore how clustering algorithms can incorporate security measures to protect the data transmitted across the network [8]. The scalability of these algorithms will be assessed, particularly regarding how cluster size and node density impact performance.

Furthermore, the relationship between clustering and data aggregation techniques will be investigated, emphasizing how effective data aggregation can further enhance energy efficiency. The review will provide information about the simulation settings and evaluation metrics employed to assess the performance of the clustering algorithms, ensuring the study's reliability and reproducibility [9].

In summary, this review offers a comprehensive overview of the current landscape of energy-efficient clustering in WSNs, equipping researchers, practitioners, and stakeholders with an understanding of the challenges, advancements, and potential directions for optimizing energy consumption in these influential networks [10, 11].

This study initiates a thorough survey of state-of-the-art clustering algorithms for WSNs, illuminating their advantages and disadvantages. The subsequent sections are organized as follows: Section II addresses the various challenges and limitations faced by WSNs, unraveling the complexities that require attention. Section III provides an extensive overview of the benefits and drawbacks of clustering in WSNs, elucidating the pathways that facilitate information flow. Section IV plays a crucial role in presenting a detailed survey of the cutting-edge clustering architectures reported in the literature. This survey is systematically organized, focusing on three key scenarios within the WSN domain: (I) Optimal Cluster Head Selection for Energy Efficiency, (II) Neighbor Discovery, and (III) Effective Techniques for Data Collection. Finally, Section V concludes the study by summarizing its essence and reinforcing the importance of clustering in WSNs. Through this exploration, we delve into the intricate landscape of WSNs, uncovering the challenges, solutions, and advancements that have shaped this dynamic field.

2. Challenges and Limitations of Wireless Sensor Networks

WSNs have experienced rapid advancements and widespread deployment, enabling a multitude of applications across various domains [12-15]. However, this proliferation is accompanied by a range of challenges and limitations that pose significant hurdles to their seamless operation. Distinguishing and overcoming these challenges is crucial for refining the efficiency, consistency, and security of WSNs. The key challenges and limitations associated with WSNs are outlined below.

2.1 Energy Scarcity

- **Power Constraints**: Sensor nodes are predominantly powered by batteries, which inherently have limited energy capacity, posing significant challenges to the longevity and efficiency of the network. Extending the operational lifetime of a network while maintaining its desired functionality is a fundamental challenge. Innovative energy management strategies are needed to ensure optimal energy usage.
- **Energy Heterogeneity**: Variability in energy levels among nodes can lead to premature node failure, resulting in uneven energy depletion across the network. This heterogeneity necessitates the development of adaptive algorithms that can dynamically respond to changing energy levels.

2.2 Communication Constraints

- **Limited Bandwidth**: WSNs typically operate in bandwidth-constrained environments. This limitation poses challenges for efficiently transmitting and receiving data, particularly in scenarios with high data traffic. Efficient communication protocols must be designed to optimize bandwidth utilization.
- **Reliability**: Wireless communication channels are inherently unreliable, and susceptible to interference and signal attenuation, leading to packet loss, increased latency, and diminished overall reliability. Data transmission dependability must be improved by implementing robust communication protocols.

2.3 Scalability Issues

- **Node Density**: Whenever the amount of sensor nodes expands, scalability becomes an issue. Effectively managing large node populations and ensuring seamless communication and data aggregation poses significant challenges that require innovative management strategies.
- **Topology Control**: Maintaining a stable network topology in dynamic environments is challenging due to node mobility, failures, and unpredictable changes in network structure. Techniques for adaptive topology management are essential to enhance network resilience.

2.4 Security and Privacy Concerns

- **Data Integrity and Confidentiality**: WSNs often handle sensitive information, making the integrity and confidentiality of data paramount. Effective security mechanisms are required to protect against malicious attacks, eavesdropping, and data tampering.
- **Authentication and Key Management**: Establishing secure communication channels and managing cryptographic keys in resource-constrained nodes present significant challenges. Robust authentication protocols are essential for securing node communications.

2.5 Quality of Service (QoS) Requirements

- **Latency**: Real-time applications, such as surveillance and healthcare monitoring, necessitate low latency. Achieving low-latency communication in WSNs, particularly in large-scale deployments, is challenging and requires optimized routing protocols.
- **Reliability**: Some applications require high reliability, which necessitates robust procedures for handling node malfunctions and ensuring uninterrupted data flow. QoS-aware routing protocols can help meet these reliability requirements.

2.6 Topology Dynamics

- **Node Mobility**: In certain applications, sensor nodes may be mobile (e.g., wildlife tracking). Adapting to dynamic topologies and maintaining connectivity in the presence of node mobility are non-trivial challenges that require adaptive routing protocols.

2.7 Resource Constraints

- **Limited Processing Power**: Sensor nodes generally possess limited processing capabilities, restricting their ability to execute complex algorithms. Efficient resource allocation and task scheduling are critical for optimizing performance and extending network lifetime.
- **Memory Limitations**: Limited memory capacity presents challenges for storing and managing data, particularly in scenarios requiring long-term data storage. Algorithms that efficiently utilize available memory are necessary to enhance data management.

2.8 Interoperability

- **Heterogeneous Devices**: WSNs may consist of heterogeneous devices from different manufacturers, leading to interoperability challenges. Standardization is necessary to facilitate seamless integration and communication among diverse sensor nodes.

Addressing these challenges necessitates interdisciplinary research efforts encompassing fields such as energy-efficient algorithms, communication protocols, security mechanisms, and adaptive networking strategies [15]. As WSNs progress and diversify in application, continuous innovations will be essential to surmount these hurdles and realize the whole potential of WSNs.

2.1 Energy-Aware Routing

Efficient and sustainable WSNs rely heavily on energy-aware routing, a critical component of their design. Given that sensor nodes frequently run on restricted energy sources, such as batteries, the selection of routing techniques is crucial for conserving energy usage and enhancing the entire network lifetime [16]. Energy-aware routing aims to intelligently direct data through a network by considering individual node energy constraints and mitigating the risk of premature node failures. Key aspects of energy-aware routing in WSNs include the following [14-17]:

- **Energy-Efficient Path Selection**: Routing algorithms prioritize selecting paths that consume minimal energy to extend the network's lifespan. Metrics such as residual energy, distance, and link superiority are considered in the path-selection process to identify routes that optimize energy usage across nodes.
- **Dynamic Routing Adaptation**: Energy-aware routing protocols incorporate adaptability to dynamic network conditions. This adaptability includes adjusting routes based on

changes in node energy levels, network topology, or environmental factors. For instance, data may be rerouted through nodes with higher energy reserves to prevent rapid energy depletion in heavily utilized nodes.

- **Load Balancing**: Distributing data traffic efficiently helps prevent energy exhaustion in specific nodes. Load-balancing strategies aim to spread data evenly among sensor nodes, thereby avoiding hotspots where certain nodes may deplete their energy more rapidly than others. This can involve dynamically redistributing data flows or employing algorithms that account for individual node energy levels in routing decisions.
- **Sleep Scheduling and Duty Cycles**: Energy-aware routing commonly includes sleep scheduling or duty-cycling techniques to preserve consumption throughout moments of idleness. Nodes may enter low-power sleep modes to extend their operational lifetime. Scheduling mechanisms that synchronize sleep cycles among nodes can maximize energy savings while minimizing communication delays.
- **Cross-Layer Optimization**: Cross-layer design involves the cooperative integration of different layers within the communication protocol stack to enhance routing decisions, considering both energy and communication requirements. More enlightened routing decisions that maximize network performance and energy efficiency may be made by integrating data from the tangible, data connection, and network levels.
- **Prediction and Estimation**: Energy-aware routing protocols may utilize predictive models or estimation techniques to anticipate the future energy levels of nodes. This information supports proactive routing decisions to avoid nodes nearing energy depletion. Predictive models can incorporate historical energy usage patterns, environmental conditions, and the current state of nodes.
- **Clustering and Hierarchical Routing**: Clustering techniques, such as Low-Energy Adaptive Clustering Hierarchy (LEACH), are often employed alongside energy-aware routing. Clustering helps organize the network into manageable groups, with designated cluster heads responsible for routing decisions. Hierarchical structures enable energy-efficient communication, reducing overall overhead and extending network lifetime.
- **QoS Considerations**: Energy-aware routing protocols must balance energy efficiency with application-specific QoS requirements. This may involve prioritizing certain data types or ensuring timely delivery for real-time applications while accommodating energy constraints.

Efforts in energy-aware routing have significantly contributed to the sustainability and effectiveness of WSNs. As research continues to evolve in this domain, innovations in routing protocols and strategies will address unique challenges posed by the energy constraints inherent in WSNs.

3. Hierarchical Routing in Wireless Sensor Networks

Hierarchical routing is a pivotal strategy utilized in WSNs to enhance efficiency, scalability, and energy conservation. In WSNs, where numerous small, energy-constrained sensor nodes collaborate to collect and disseminate information, hierarchical routing provides a structured organizational framework [18]. This framework significantly optimizes network performance and sustainability.

The key features and considerations associated with hierarchical routing in WSNs include the following [16-19, 22-25]:

3.1 Cluster Formation

Hierarchical routing involves organizing sensor nodes into clusters, creating a multi-tiered structure. Sensor nodes under the direction of a specified cluster head (CH) comprise each cluster. The CH is in authority for managing intra-cluster communication, accumulating information from other nodes, and forwarding the summarized information to higher-level clusters or sink nodes. This organizational structure streamlines data transmission and reduces communication overhead.

3.2 Cluster Head Selection

Efficient CH selection is crucial for the success of hierarchical routing. Protocols like LEACH employ probabilistic methods or switch up the cluster head's role to ensure an equitable distribution of energy usage across nodes. This periodic reselection of CHs helps prevent specific nodes from depleting their energy prematurely, thereby enhancing the network's overall lifespan.

3.3 Energy-Efficient Data Aggregation

Hierarchical structures facilitate energy-efficient data aggregation within clusters. Information from member nodes is aggregated by cluster heads before being sent to sinks or higher-level clusters. By reducing the volume of data transferred across long distances, this aggregation minimizes communication overhead and energy usage. The network saves energy by processing data locally, which lowers the amount of data transferred to the sink.

3.4 Scalability

Hierarchical routing significantly enhances the scalability of WSNs. By organizing nodes into manageable clusters, the network can add more nodes. This hierarchical structure minimizes the impact of individual nodes on the overall network, facilitating the expansion of WSNs to cover larger geographical areas without overwhelming network resources.

3.5 Reduced Communication Overhead

Intra-cluster communication is typically more frequent and energy-efficient than direct communication between individual nodes and sink nodes. Cluster heads serve as intermediaries, effectively reducing overall communication overhead. Additionally, shorter communication distances within clusters mitigate the effects of channel interference and signal attenuation, further enhancing data transmission reliability.

3.6 Fault Tolerance

Hierarchical routing enhances fault tolerance by localizing the impact of node failures. If a node within a cluster experiences a malfunction, the cluster head is capable of reorganizing the cluster with minimal disruption. The hierarchical structure facilitates the identification and management of faulty nodes, contributing to the robustness of the network.

3.7 Adaptability to Node Heterogeneity

Hierarchical routing accommodates node heterogeneity by allowing for varying degrees of energy capacity and processing capabilities within clusters. Nodes with higher energy reserves or superior processing capabilities can assume more critical roles, such as serving as cluster heads or managing complex computations, thus optimizing resource utilization across the network.

3.8 Enhanced Security

The hierarchical structure introduces an additional layer of security by localizing the impact of compromised nodes. Security measures can be more effectively implemented within clusters to protect against attacks and unauthorized access. Cluster heads can employ encryption and authentication mechanisms to secure data transmission, improving the security of the entire network.

3.9 Application-Specific Optimization

Hierarchical routing allows for customization based on specific application requirements. Different protocols or parameters can be adjusted to optimize network performance for particular applications. For instance, certain applications may prioritize minimizing latency, while others may emphasize energy conservation, thereby tailoring the routing strategy to specific operational needs.

In conclusion, hierarchical routing in WSNs provides an effective organizational framework for addressing challenges associated with energy conservation, scalability, and communication efficiency. As WSNs continue to evolve and find applications across diverse domains, further research and innovation in hierarchical routing protocols are essential to enhance the overall effectiveness and sustainability of these networks.

3.1 Pros and Cons of Clustering in WSNs

Clustering in WSNs is a widely embraced strategy that comprises bringing together sensor nodes into clusters to recover network efficiency, scalability, and resource utilization [12]. While clustering offers several advantages, it also presents certain challenges and tradeoffs. The following outlines the advantages and disadvantages of clustering in WSNs [11-19]:

Pros

- **Energy Efficiency**: Clustering promotes local communication within clusters, significantly reducing communication distances. This results in energy savings, as shorter communication distances require less power for data transmission. Energy-efficient clustering is vital for extending the operational period of a network, which is critical in energy-constrained sensor nodes.
- **Scalability**: By organizing nodes into manageable groups, clustering enhances the scalability of WSNs. This hierarchical structure simplifies network management, allowing for the addition of more nodes without overwhelming the system. Scalability is essential in scenarios where WSNs must cover large geographical areas or accommodate a high density of sensor nodes.
- **Reduced Communication Overhead**: Intra-cluster communication is more frequent than inter-cluster communication, leading to a reduced overall communication overhead. Cluster heads aggregate data locally before transmitting summarized information to higher-level clusters or sinks. This reduction in communication overhead minimizes congestion,

improves network efficiency, and mitigates the effects of interference and signal attenuation.

- **Fault Tolerance**: Clustering inherently provides fault tolerance by localizing the impact of node failures. Whenever a node fails, then the CH adapts and reorganizes the cluster without affecting the entire network. Fault tolerance is crucial in dynamic environments where sensor nodes may experience failures due to environmental conditions or hardware issues.
- **Adaptability to Node Heterogeneity**: Clustering accommodates node heterogeneity by allowing nodes with varying energy reserves or processing capabilities to coexist within clusters. This adaptability optimizes resource utilization, enabling efficient collaboration by assigning roles based on individual node characteristics.

Cons

- **Overhead in Cluster Formation**: The process of forming clusters and selecting cluster heads incurs an initial overhead. This overhead can be significant, particularly in scenarios where frequent cluster reconfiguration is necessary. Reducing the overhead involved in forming clusters is particularly difficult, especially in applications with fluctuating network conditions.
- **Uneven Energy Depletion**: If the CH selection process is not consistently circulated, it can lead to uneven energy depletion among cluster heads. This premature failure of specific nodes can adversely impact overall network performance. Designing algorithms that ensure equitable energy usage among cluster heads is a critical challenge in energy-aware clustering.
- **Complexity in Implementation**: Implementing and managing clustering algorithms introduces complexity to the network architecture. Managing this complexity may call for higher computational power and the use of advanced protocols. The challenge lies in effectively balancing the advantages of clustering with the difficulties of implementing it in real-world applications.
- **Suboptimal Performance in Dynamic Environments**: Clustering may exhibit suboptimal performance in highly dynamic environments where nodes frequently change positions or experience mobility. The reorganization of clusters in response to dynamic changes can introduce latency. Developing adaptive clustering algorithms that respond effectively to dynamic environmental conditions remains a challenge.
- **Impact of Cluster Head Failure**: The failure of a cluster head can disrupt intra-cluster communication and may necessitate reconfiguration. This can introduce transient periods of increased energy consumption and communication delays. Implementing mechanisms to efficiently handle and recover from cluster head failures is crucial for maintaining network stability.

In summary, while clustering in WSNs offers substantial benefits, it also introduces challenges related to overhead, energy distribution, implementation complexity, adaptability to dynamic environments, and managing cluster head failures. Ongoing research aims to address these challenges and optimize clustering algorithms for diverse applications and network conditions.

4. Data Collection in Wireless Sensor Networks

4.1 Overview of Data Collection in WSNs

The paramount task in WSNs revolves around data collection, wherein each sensor node transmits sensed data to a designated sink that serves as the user interface. Data transmission occurs through multi-hop paths, with intermediate nodes facilitating the relay of information. Notably, sensor nodes closer to the sink bear a higher energy consumption burden because they relay data from other nodes. Numerous studies have employed mobile sinks to mitigate this problem by reducing the number of hops and distributing energy consumption. Previous investigations concentrated mostly on network limitations and assumed that nodes with sensors would send just one packet of data to the mobile sink. In contrast, our research leverages an unmanned drone as a portable sink, accounting for tiny sensors that communicate multiple data packets.

4.2 Algorithms for Efficient Data Collection

To tackle the issue of efficient data collection, this study introduces two GRASP-based heuristics designed to develop optimal routes for drones tasked with data collection. Our main goal is to minimize the overall time required to collect all data, considering the drone's limited flight time. Additionally, our heuristics ensure that the drone spends minimal time within each sensor node's radio range, allowing for optimal data transmission. This was achieved by selecting strategic locations for the drone to hover and gather data from within the monitored area. The proposed heuristics effectively reduced the data collection time and determined the shortest path for the drone, resulting in an overall shorter trip time. Through simulations, we demonstrate that our GRASP-based heuristics outperform the previous greedy algorithm, especially in cases where each sensor node holds a significant amount of data [20].

4.3 Challenges of Data Gathering with Mobile Sinks

In this study, the challenges associated with data gathering in WSNs employing mobile sinks (MSs) in realistic environments are characterized by obstacles such as rocks and hills. Earlier research frequently simplified obstacle scenarios and overlooked the complexities present in real-world sensing environments. This study presents a novel algorithm known as Mobile Sink-based Data Harvesting in Real-world Sensing Fields (MSDRF) [21]. This approach involves preprocessing the area by dividing it into cells to evaluate the costs associated with the movement of the mobile sink across various regions. The configuration of the network contains separate phases for clustering, both employing advanced artificial intelligence algorithms. Simulation results indicate that the MSDRF markedly enhances energy efficiency and minimizes energy variation among nodes when compared to earlier algorithms.

4.4 Energy and Delay Efficient Data Acquisition

Using a mobile sink for data collection in WSNs offers considerable benefits, especially in large-scale deployments. Unlike static sinks that depend on multi-hop forwarding, a mobile sink moves through the sensing area, significantly lowering the energy usage of sensor nodes. However, identifying the best stopping points for the mobile sink and creating a trajectory that minimizes delays presents significant challenges. To tackle these issues, this paper presents the Energy and Delay Efficient Data Acquisition (EDEDA) technique [22]. EDEDA effectively partitions the sensor area into virtual grids, selects specific grid cells as visiting points (VPs), and ensures that the mobile sink remains in these locations for single-hop data collection from neighboring grid cell heads. Simulation results indicate that EDEDA outperforms existing routing protocols, providing benefits in energy efficiency, throughput, and data collection latency.

4.5 Compressive Data Gathering with Sleep Scheduling

Compressive Data Gathering (CDG) provides a practical solution for decreasing data transmission and the associated energy usage in WSNs. The incorporation of sleep scheduling into the CDG framework enhances energy efficiency even further. Nonetheless, many strategies often rely on optimization methods that lead to an exchange of control messages. On the other hand, distributed methods often rely on stochastic decisions, risking premature energy depletion at certain nodes. To address these challenges, this study introduces a reinforcement-learning-based sleep scheduling algorithm for CDG (RLSSA-CDG) [23]. We present a formal model for active node selection using a finite Markov decision process. Our approach employs model-free Q-learning to determine the most effective decision strategy. The reward function considers both remaining energy levels and sampling uniformity, which promotes balanced load distribution and accurate data reconstruction. Our distributed algorithm, known as RLSSA-CDG, requires minimal control message exchanges but has been shown to outperform existing methods.

4.6 Fault-Tolerant Cluster-Based Routing Technique

WSNs encounter significant challenges concerning energy consumption, which affect both network longevity and communication capabilities. Clustering is a well-established approach for minimizing energy usage in WSNs, where CHs gather data and relay it to the sink node. However, failures in cluster heads can disrupt data transmission. The work gives a fault-tolerant cluster-based routing strategy through the Battle Royale Optimization (BRO) algorithm for selecting backup cluster heads (BKCHs) and employs a modified Particle Swarm Optimization (Mod PSO) 【47]. The suggested approach includes an aggregator node (AG) to facilitate data transfer between clusters. The findings demonstrate that this technique effectively reduces both delay and routing overhead while enhancing the overall lifespan of the network.

4.7 Addressing Sink Mobility Challenges

WSNs relying on static sinks face vulnerabilities such as the sinkhole problem, prompting researchers to investigate sink mobility as a potential solution. This paper [24] presents a new and effective data collection method that utilizes the Jaya algorithm to address obstacles related to finding the best routes for mobile sinks. The developed method optimizes both path length and energy usage for the mobile sink, surpassing existing algorithms for path length, rendezvous points, energy consumption, and overall network longevity.

4.8 Proposed Data Delivery Model (PDDM)

The integration of WSNs with the Internet of Things (IoT) encompasses devices with varying resource configurations. Effective data collection models are crucial for handling the data generated within the network. This study presents a novel data delivery framework referred to as the PDDM. Results indicate significant enhancements, with the PDDM achieving a 50.24% increase in throughput, an 89.9% improvement in PDR compared to traditional event-driven data delivery models, and a 74.67% reduction in end-to-end delay [25].

4.9 Summary of Related Literature

Table 1 presents a comprehensive review of the related literature focusing on various strategies and algorithms for efficient data collection in WSNs. This table summarizes the title, authors, year of publication, main findings, limitations, and software used in the reviewed studies.

Reference Number	Main Findings	Limitations	Software Used
[3]	Energy efficiency compared between techniques, lack of focus on sensor node mobility, insights into best techniques for power saving	Sensor node mobility especially in single mobile sink node.	MATLAB
[5]	Effectiveness of energy-efficient clustering algorithms (HOCK and HECK) in improving network lifetime compared to existing methods	Lack of finding out single node clusters	MATLAB
[6]	The proposed CEEC protocol outperforms classical clustering mechanisms in terms of network lifetime, energy consumption, and throughput.	Not considering multi-hop CH.	MATLAB R2022
[9]	Integrating MFO, SSA, or WOA algorithms into clustering protocols significantly extends WSN lifetime and improves network throughput.	CH election is done in a traditional way which is a time-consuming process	MATLAB R2022
[10]	The proposed routing protocol EAOCSR shows superior performance in energy utilization, throughput, network lifetime, stability, and security.	Secondary CH is elected without any conditions	MATLAB
[11]	Novel SGO-based unequal clustering model to attain energy efficiency by constructing clusters of unequal sizes	More message drops in the simulation	NS 2.34

Reference Number	Main Findings	Limitations	Software Used
[12]	The proposed MFA-AOA optimized protocol enhances lifespan and reduces energy consumption compared to existing techniques.	CH selection approaches ignore long-term inclusion requirements	MATLAB 2019b
[13]	ECOR algorithm outperforms I-LEACH in terms of CH distribution and energy consumption	CH is elected without any criteria	NS-2.35
[14]	Provides insights for analyzing existing routing protocols to mitigate the hot-spot problem	Neighbor detection is lacking	NS 2
[15]	The CSPOC-GFLR technique achieved reduced energy utilization and improved lifetime and stability.	Not considering the distance parameter	NS 3.25
[16]	EE-MOOA improves the Butterfly Optimization Algorithm, achieving 99.12% energy efficiency for 100 nodes	Network lifetime improved but the message transmission rate is less	MATLAB 2019b
[18]	Significant improvement in network lifetime, packet delivery ratio, throughput, and delay; introduces energy-aware routing	Dependence on variable values and fitness function outcomes; need for lightweight prediction algorithm	NS2
[19]	ITSA-UCHSE technique used for hotspot elimination and uneven energy dissipation	Takes more time to form a cluster	MATLAB 2019b
[20]	Significantly improves energy efficiency, reduces transmission delays, and increases data delivery rate through stable CH selection.	Single-node clusters are not considered.	MATLAB 2019b
[22]	Four major processes: Quad tree-based network construction, energy-efficient clustering, RL-based duty cycling, and secure multipath routing	Not considering the mobility of sensor nodes, lack of fault tolerance	NS-3.26

Reference Number	Main Findings	Limitations	Software Used
[24]	EACODT algorithm improves energy efficiency through battery amplification	Not considering distance as a parameter	MATLAB 2019b
[25]	LEACH algorithm for CH selection; high PDR achieved by the LEACH-ISMO method	Need to develop adaptive paths using hybrid optimization algorithms	NS-2.34

4.10 Conclusion

This section has explored various strategies and algorithms employed for effective data collection in WSNs, addressing challenges such as energy consumption, mobility of sensors, and the integration of mobile sinks. The proposed models and algorithms significantly enhance network performance, prolonging network lifetime and improving data collection efficiency. The literature reviewed highlights the ongoing advancements and the importance of developing robust techniques to meet the challenges posed by real-world WSN applications.

5. Conclusion and Future Work

This research significantly contributes to addressing key challenges in WSNs by focusing on enhancing energy efficiency through innovative cluster head selection, routing algorithms, and neighbor discovery mechanisms. These efforts aim to prolong the lifespan of WSNs, minimize energy consumption, and improve network efficiency. The study showcases a diverse array of algorithms, including Ultra-Scalable Ensemble Clustering and Grey Wolf Optimization, which highlight the adaptability of computational intelligence and metaheuristic approaches in various operational scenarios. Additionally, the use of reinforcement learning in sleep scheduling and data acquisition strategies presents a comprehensive approach to tackling energy challenges during data transmission. Experimental evaluations demonstrate that the proposed models exhibit superior performance, indicating their potential for practical implementation in real-world settings. Future research may explore advanced algorithms based on Grey Wolf Optimization for cluster head selection, incorporating factors like residual energy to further enhance energy-efficient data delivery.

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