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Optimizing Wireless Sensor Networks: A Survey of Clustering Strategies and Algorithms

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Abstract – Wireless Sensor Networks (WSNs) are essential for real-time data collection and monitoring in various fields, such as environmental sensing, healthcare, industrial automation, and military surveillance. Energy management is very important to the WSNs lifetime and performance since the sensor nodes use batteries and often deployed in areas that are difficult to access. Clustering has become a vital technique in the control of energy demands with the various sensor nodes being grouped in several clusters under the supervision of a cluster head. Clustering helps in the distribution of energy evenly in the network minimizing the number of unnecessary transmissions. This study highlights clustering techniques and methods that have been developed for WSNs, together with their objectives, concepts, and consequences on the performance of networks. The clustering strategies are categorized by employing several methods; these are hierarchical, distributed, centralized, and hybrid approaches. Every clustering technique has its benefits and drawbacks. The choice of the best-fit approach determines on the actual needs of the WSNs. The discussion explains the strategies of different algorithms, advantages, and disadvantages. Moreover, the issues discussed in the study address the present-day concerns and the future research trends of enhancing clustering algorithms of WSNs. The presented work contributes to the understanding of how to choose and enhance clustering approaches to enhance WSNs effectiveness and longevity. This study serves as a helpful source of knowledge that can encourage the further development of the enhancement of clustering algorithms for WSNs in response to modern technology needs.

Index Terms – Wireless Sensor Networks, Clustering Strategies, Clustering Algorithm, Optimization Techniques, Energy Efficiency, Network Longevity.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) occupy a strategic position in the field of gathering data and supervising various environmental processes for real-time interaction with the physical world [1]. This networks system involves basically small nodes widely dispersed within a large area that has the ability to capture, process and transmit data to an analysis center. Through management of the energy resources of WSNs key emphasis is placed in the fact that most of the sensor nodes are located in inaccessible places and may be powered by batteries or in hostile areas where battery replacement is impossible [2]. WSNs are an integral component of modern technological advancements, particularly in the field of industrial automation, environmental monitoring, healthcare systems, and infrastructure management [3]. These networks are designed to operate in a distributed nature, with multiple sensor nodes strategically placed in the environment being monitored [4]. WSNs are engineered to consume low power, allowing them to function on limited battery power for extended periods of time, making them highly efficient and cost-effective. One of the keys defining features of WSNs is their scalability. They can be easily deployed and expanded with many sensor nodes to cover a wide area or monitor various parameters. This makes them adaptable to diverse monitoring needs and ensures comprehensive data collection across different environments [5]. Furthermore, the ability of sensor nodes to operate in harsh and remote environments makes WSNs invaluable for applications like wildlife monitoring, disaster management, and structural health monitoring. These networks can thrive in outdoor or inaccessible regions where conventional wired networks are not practicable or unfeasible [6].

In summary, Wireless Sensor Networks are scalable and easily deployable networks that operate in a distributed manner. They are energy-efficient, allowing for long-term operation on limited battery power. WSNs can operate in challenging environments and gather data from different sources, aggregate it, and forward it to a central area. Moreover, WSNs are proficient in data aggregation, wherein sensor nodes can gather information from different sources and aggregate it prior to sending it on the sink node. This not

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only decreases the quantity of data to be transferred but also conserves energy, making WSNs highly efficient in resource management. Despite their energy consumption, memory storage, and bandwidth limitations, WSNs have proven to be crucial in many fields as agriculture, environmental noise assessment, and library air quality monitoring.

Clustering has become an important approach that is widely used to minimize the energy consumption in WSNs. In clustering, the cluster of sensor nodes is developed with each cluster head that facilitates the intra-cluster communication and send the acquired data to the central station; thus, minimizing redundancy of data and making an equal distribution of the load amount of data transfer to network [7]. The effectiveness of the clustering methods used dramatically affects the entire lifespan of the WSN network, the quality of the collected data, and its reliability. The selection of clustering technique affects all the parameters such as efficiency, scalability and robustness of WSNs. Many clustering techniques have been proposed and exist and all of them are different from one another by their strategies of creating and supervising cluster [8]. These algorithms differ in the level of complexity, energy consumption, and collaboration when working in different networks. For example, some algorithms aim at the reduction of energy consumption within clusters, while keeping the load balanced or improving the network's reliability to node failures [9]. Different clustering algorithms offer various methods for improving energy efficiency, load balancing, and network reliability.

The primary focus of this research is to explore and compare different clustering algorithms used in WSNs, with a special emphasis on their optimization techniques and impact on network performance. By analyzing existing clustering strategies, this research aims to give an updated view of the strengths and weaknesses of various algorithms and discuss recent developments that address the challenges of dynamic and heterogeneous WSNs. The goal is to identify clustering approaches that are best suited for improving the efficiency, scalability, and robustness of WSNs in real-world applications.

This research contributes to the growing body of knowledge in WSN optimization by examining both classical and modern clustering algorithms. Given the ever-increasing need for dependable and energy-effective networks in industries such as agriculture, environmental monitoring, and disaster management, the insights gained from this study have practical significance in enhancing the design and deployment of WSNs.

1.1. Research Motivation

With the increasing deployment of WSNs, optimizing the network's performance particularly in terms of energy efficiency, scalability, and reliability has become a critical area of research.

Clustering is useful for cutting down energy by uniting the sensor nodes into group where one single node is elected to be in charge of the gathering of data and messaging. This not only reduces data redundancy but also balances the energy load across the network, extending its overall lifespan.

Despite the benefits of clustering, existing algorithms vary widely because of energy efficiency, scalability, robustness, depending on the network's design and environmental conditions. Additionally, the increasing complexity of modern WSNs characterized by dynamic and heterogeneous nodes presents new challenges that traditional clustering approaches may not adequately address.

The purpose for this study lies in the need to comprehensively review and assess the existing clustering algorithms in WSNs, with a focus on identifying methods that optimize network performance, particularly in energy-constrained environments. By surveying the latest advancements in clustering strategies, this study aims to bridge the gap between current solutions and the growing demands of real-world WSN applications, where efficiency, scalability, and reliability are paramount.

1.2. Objectives

1. To review and classify existing clustering techniques in WSNs.
2. To evaluate the impact of clustering algorithms on network performance.
3. To highlight recent advancements and trends in clustering for heterogeneous WSNs.
4. To identify key challenges and future directions in WSN clustering.

Organization of the paper as follows: Section 2 describes the related work of clustering in WSN, basic architecture of WSN, an overview of WSN, and key challenges in WSN. Section 3 gives a comprehensive description of the clustering in WSN and challenges in clustering. Section 4 and 5 presents clustering strategies with the recent advancement of algorithms. Section 6 shows the comparison of clustering algorithms. Section 7 and 8 provides the results and discussion with future works and challenges. Finally, section 9 concludes the paper.

2. RELATED WORK

As for the recent years a significant proportion of the research has been focused on the enhancement and fine tuning of clustering techniques for WSNs. All these strategies are meant to improve energy utilization, reliability and flexibility since these aspects are critical to the deployment of WSNs.

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New development in this area has seen the formulation of several energy effective clustering algorithm aimed at improving on the network lifetime. For instance, Prakash & Pandey (2023) put forward PSO-EECS, the energy-efficient clustering scheme employed particle swarm optimization for WSNs to improve the energy efficiency and prolong the network life-cycle. Energy efficient clustering scheme strengthens LEACH protocol by adopting constant energy load sharing among cluster heads nodes in addition to optimal formation of clusters. It Implements constant energy load sharing among cluster head nodes. EECS improves energy distribution across the network and total network lifespan [10]. In the same category, the Distributed Weight based Energy Efficient Hierarchical Clustering (DWEHC) aims at minimizing the intra-cluster and inter-cluster communication costs to enhance the required energy conservation. Jha et al. (2022) suggested a distributed energy-based clustering technique for WSNs to prolong network lifespan and enhance transmission of data to the base station. It introduces a multi-parameter weighted scalarization function with an innovative approach to weight calculation employing the analytical hierarchy method for selection of optimal cluster head. It reduces overall energy usage in the network and achieves more balanced cluster sizes [11]. Metaheuristic algorithms were studied to identify how the use of these techniques can be useful for optimizing the formation of clusters and head selection in WSNs. Rawat & Chauhan (2021) suggested a particle swarm optimization-based energy-efficient clustering (PSO-EEC) protocol for WSN to enhance network lifespan and performance. The use of Particle Swarm Optimization (PSO) as per clustering the parameters being residual energy, distance to sink node, and node degree. In comparison to current methods in PSO, the suggested scheme significantly increases the longevity of the network (by up to 238%) and stability period (by up to 396%) [12]. Maheshwari et al. (2021) introduced an optimization of clustering using two meta-heuristic algorithms Ant-Colony Optimization (ACO) and Butterfly Optimization are proposed in this study with a view to enhancing network longevity and reducing energy consumption. The selection of cluster head depends on the residual energy, distance from the node to the base station, centrality, and node degree, however, the routing depends on the distance, residual energy and node degree. The proposed methodology outperforms conventional techniques LEACH, DEEC and latest methods (CRHS, FUCHAR, BERA, ALOC, CPSO, FLION) about the number of live and dead nodes, energy use, and transmission of data to the main station and adapts well to changing network topologies [13]. To reduce the level of uncertainty in the clustering results fuzzy logic has been incorporated in the process. Ab Rahman et al. (2020) suggested a fuzzy logic RSSI clustering algorithm that takes into consideration of factors like energy level, node degree centrality and node density in the selection of the cluster heads. This RSSI-based scheme aims to address the lack of attention given to signal strength in previous selection methods of Cluster Head. The simulation outcome demonstrate that the recommended strategy significantly extends network lifetime and slows down node death compared to existing protocols like Multi-Tier Protocol (MAP) and Stable Election Protocol (SEP) [14]. Subsequent to that, Verma et al. (2020) developed a new FLEC approach which is based on fuzzy logic to cluster the Homogeneous WSN, adapting the cluster structure based on node mobility patterns. FLEC enhances the LEACH-Fuzzy protocol by incorporating median energy-based chance and median threshold for selection of cluster head, which outperform over LEACH-Fuzzy, DEEC and LEACH protocols [15]. Hamaali et al. (2023) developed a hybrid clustering approach that connects PSO algorithm with using K-means algorithm, comparing elbow and silhouette methods for determining the ideal number of clusters across different network sizes in WSN. The proposed approach, termed PSO-K-means, outperformed traditional clustering algorithms based on energy usage and data transmission ratio [16]. Mostafavi & Hakami (2020) suggested a new clustering algorithm for WSN called ARO-WSN (Approximate Rank-Order WSN), which combines hierarchical and distance-based clustering approaches. ARO-WSN introduces a new rank-order distance function into the procedure for agglomerative hierarchical clustering; rankings are based on the distance between the nodes and their neighbors on the WSN. Simulation studies indicate that developed ARO-WSN surpasses various clustering algorithms as LEACH, LEACH-C and LEACH with fuzzy criteria, significantly improving network lifetime based on both first node death (up to 85%) and last node death (up to 67%) criteria [17].

These recent studies highlight the diverse range of optimization techniques and algorithms being applied to clustering in WSNs, including metaheuristic algorithms, fuzzy logic, game theory, machine learning, distributed optimization, and multi-objective optimization. The proposed algorithms and frameworks aim to address various challenges and optimize specific performance metrics like energy efficiency, scalability, network lifetime, and data delivery reliability.

2.1. Wireless Sensor Network: An Overview

WSNs are the networks consisting of small, autonomous devices called wireless sensor nodes [18]. These nodes are fitted with sensors, wireless connectivity and processors, allowing these to detect and gather information from their surrounding environment [19]. These networks are self-organizing, meaning that the nodes can communicate with each other and coordinate their actions without the need for centralized control. A basic architecture of WSN shown in the Figure 1.

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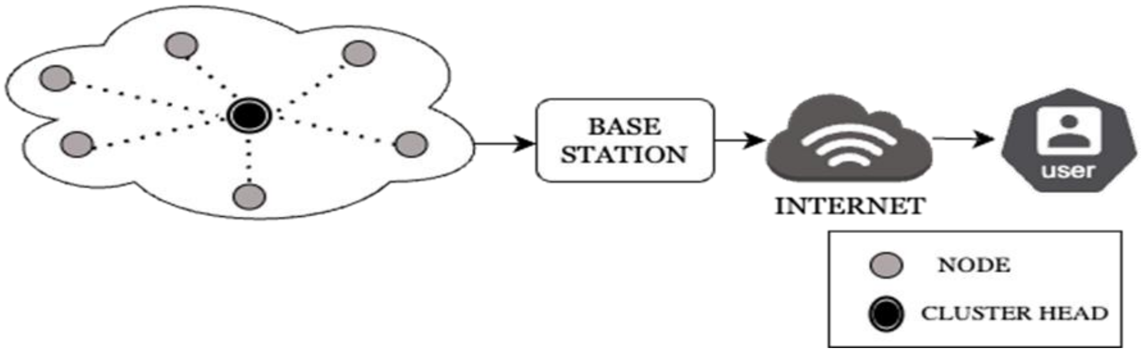

Figure 1 Architecture of WSN

Sensor nodes are placed in a particular region in order to collect information to be sent to a base station [20]. Clustering on the other hand consists of partitioning the sensor nodes into groups or rather clusters and the head of each cluster. Each cluster head is assigned with the task of managing the communication within a given cluster and forwarding the information towards the base station [21]. A WSN architecture generally consists of three main components: sensor nodes, base stations (or sink nodes), and a user interface or application.

Sensor Nodes: Sensor nodes are typically small devices with at least one sensor, a microcontroller, radio transceiver, and energy source commonly a battery. They are responsible for perception and data acquisition from the surroundings, data processing in a rather basic way, and transmitting the information through the wireless medium to other nodes or to the sink node [22].

Base Stations (Sink Nodes): Base stations are interfaces of the sensor nodes and can be viewed as a connection point that connects sensor nodes to a user interface or an application. They gather information from the nodes that are sensors either directly or indirectly and, in some cases, may process the information before forwarding it to other networks or systems [23].

User Interface or Application: The user interface or application is the part that communicates with the WSN, get the data, and may involve data processing, data representation, or even making decisions based on the received data [24].

2.2. Types of WSNs

WSNs can be categorized into many kinds according to various characteristics and application requirements. These are some basic types of WSNs shown in Figure 2.

Terrestrial WSNs: These are the most frequently used WSNs that are deployed on the surface of the Earth or on the land for uses such as environmental monitoring, precision agriculture, and industrial applications. For instance, according to the deployment environment, Terrestrial WSNs can be divided into outdoor and indoor WSNs; each of them has its own challenges and limitations [25].

Underground WSNs: Underground WSNs concerns with monitoring of condition below the surface of the earth include soil moisture, underground water level and seismic activities. That would include issues such as node placement, messaging through soil or rock, and power issues due to constrained sunlight [26].

Underwater WSNs: Underwater WSNs are used for monitoring underwater environments, including ocean and lake monitoring, offshore exploration, and underwater surveillance. They face unique challenges like limited bandwidth, high propagation delay, and node mobility caused by water currents [27].

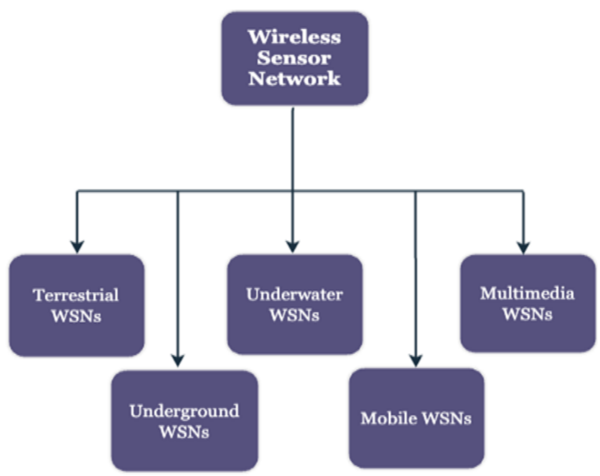

Figure 2 Types of WSN

Multimedia WSNs: These networks incorporate multimedia elements like camera and microphone with the sensor nodes for multimedia data acquisition and transfer [28]. Multimedia WSNs are employed in surveillance-related applications, traffic monitoring, and environmental monitoring with audio and video data.

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Mobile WSNs: Mobile WSNs involve mobile sensor nodes or mobile data collectors (sinks) that move within the network. These networks include target tracking, wildlife, and disaster management scenarios where mobility is important for coverage and data gathering [29]. The process of proper selection of different kinds of WSNs highly depends on the application needs, the environment in which WSNs is to be deployed, the nature of the data and the expected performance of the WSN. Also, the kind of WSNs being used may necessitate different protocols, architectural framework, and even optimization procedures that are different from others due to the various challenges it comes with [30].

2.3. Characteristics of WSNs

- Distributed nature: WSNs constructed by multiple sensor nodes that are distributed in the environment being monitored [31].
- Low power consumption: WSNs are expected to run on low energy sources for longer durations[32].
- Scalability: A significant quantity of sensor nodes can be added in WSNs, and developments can be made to cover a large area or to monitor different parameters. Sensor nodes by their nature are small, low-cost devices, and hence the amount of processing power and memory that can be included in them is also small. Resilient for use in rough and difficult to reach areas; WSNs are normally used in areas that are unsuitable for wired networks [33].
- Data aggregation: In a WSN, sensor nodes may receive data from several sources and then jointly forward the data to the sink node, and this section shows that this process lowers the quantity of energy used in the network [34].

2.4. Applications of WSNs

WSNs are applied in many areas of the domain due to their capability of observing the physical environment in order to gather information [35]. Here are some common applications of WSNs along with an illustrative Figure 3.

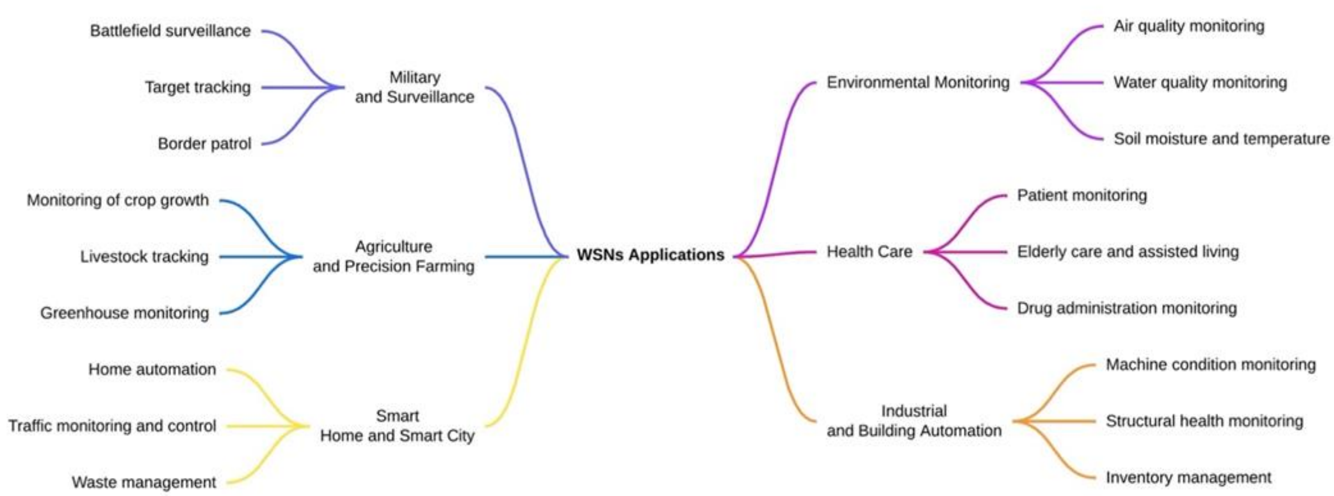

Figure 3 WSNs Applications

2.5. Key Challenges in WSNs

WSNs face numerous major challenges because of the inherent resource constraints of sensor nodes as well as the distributed nature of the network [36]. Here are some of the primary challenges in WSNs:

Energy Constraints: Sensor nodes are generally low energy devices that are powered by batteries with limited energy capacity. Replacing or recharging batteries can be impractical or infeasible, especially in large-scale deployments or harsh environments [37]. Efficient energy management and energy-aware protocols are crucial for prolonging the network's operational lifetime [38].

Limited Computational and Storage Capabilities: Sensor nodes have limited computational power and memory resources, constraining their ability to perform complex data processing and storage operations [39]. This limitation necessitates the development of lightweight algorithms and protocols tailored for resource-constrained devices.

Network Scalability: WSNs can consist of hundreds or thousands of sensor nodes, posing challenges in terms of scalability. When the network area rises, issues such as routing complexity, data management, and network organization become more significant. Scalable protocols and architectures are essential for efficient operation in large-scale deployments [40].

Node Mobility and Topology Changes: In certain applications, sensor nodes or monitored targets may be mobile, leading to dynamic network topologies. Protocols and algorithms must adapt to these topology changes and ensure reliable data delivery and network connectivity [41].

Data Aggregation and Fusion: Sensor nodes often generate redundant or correlated data, necessitating efficient data collections and integration methods to decrease the quantity of transmitted data and conserve network resources [42].

Fault Tolerance and Reliability: Numerous variables, including hardware problems, the surrounding environment, and depletion of batteries, may cause sensor nodes to malfunction. Reliable delivery of data and operation of a network in the face of failures of nodes necessitates the use of fault tolerant protocols and redundancy [43].

Security and Privacy Concerns: WSNs are susceptible to various security threats, including eavesdropping, data tampering, and denial-of-service attacks [44]. Encryption, identification, and access control are some examples of robust security measures, are essential to protect the safety, integrity, and accessibility of the data and network [45].

Bandwidth Constraints and Communication Overhead: WSNs often operate in bandwidth-constrained environments, and the wireless communication among sensor nodes can be energy-intensive [46].

Deployment and Maintenance Challenges: WSNs are frequently employed in severe environments or inaccessible environments, making it difficult to maintain and replace sensor nodes.

Integration with Other Technologies: As WSNs become more prevalent, integrating them with other emerging technologies, as the IoT, cloud computing, and edge computing, becomes crucial for enabling seamless data exchange and interoperability across different systems and platforms [47].

Addressing these challenges requires innovative solutions at various levels, including hardware design, network protocols, data processing algorithms, and system architectures. Ongoing research efforts aim to develop energy-efficient, scalable, reliable, and secure WSNs to enable their widespread adoption and deployment in various application domains.

3. CLUSTERING IN WSNS

Clustering in a WSNs describes the method used to arrange sensor nodes into clusters. based on certain criteria such as spatial proximity, energy levels, or communication range [48]. it is a technique that has proven to be particularly useful in this context, as it can aid in enhancing the scalability, data aggregation, and energy efficiency of these networks. Clustering is essential to improving the effectiveness and extending the lifetime of WSNs. The key roles and benefits of clustering in WSNs includes in the Figure 4.

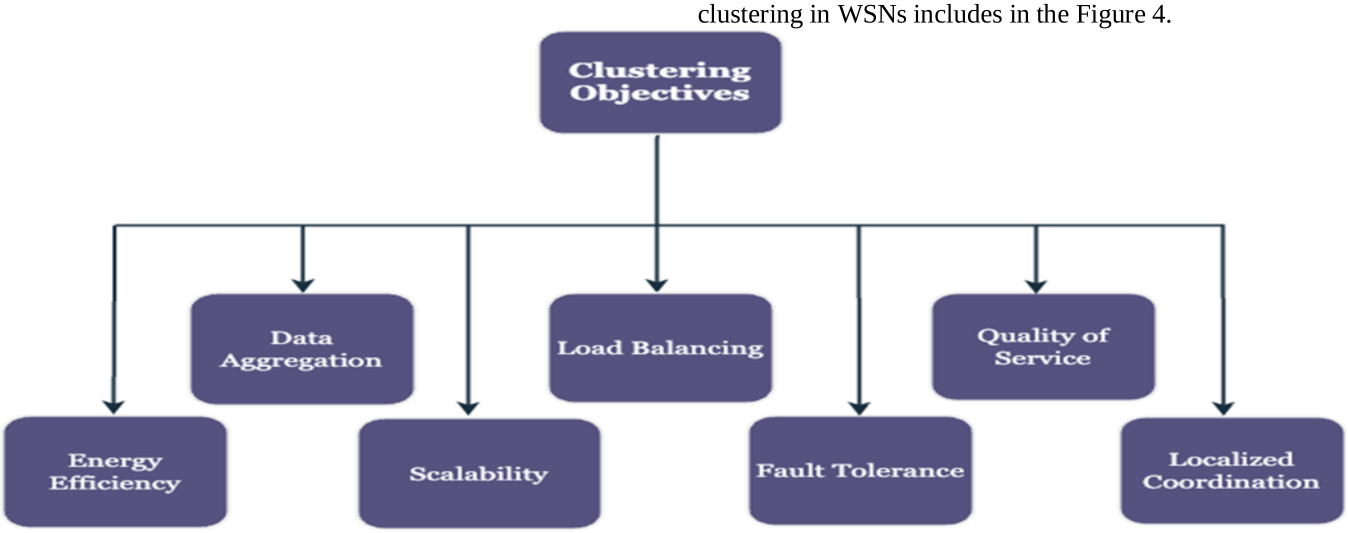

Figure 4 Clustering Objective

Energy Efficiency: Clustering is primarily employed to improve energy efficiency in WSNs. By organizing nodes clustered together and assigning a cluster head for every cluster, the demand for extended transmissions from individual nodes to the sink node is reduced [49]. Sensor nodes only need to transmit information to each of their Cluster Heads, which then combine and proceed the data to the sink node, decreasing overall energy usage and prolonging network lifetime [50].

Data Aggregation and Fusion: Cluster heads can gather data and fusion techniques on the data received from their cluster members. This helps eliminate redundant data transmissions and decreases the amount of data which required to be transferred to sink node, thereby conserving energy and bandwidth resources.

Scalability: Clustering facilitates the efficient organization and management of large-scale WSNs. As network capacity increases, clustering assists in breaking the network to smaller, easier to regulate groups, boosting scalability and decreasing the overhead involved with routing and data distribution [51].

Load Balancing: Clustering can distribute the energy consumption and communication load among different nodes by rotating the role of the cluster head. This prevents the premature depletion of specific nodes and promotes a more uniform energy consumption across the network, enhancing overall network lifetime [52].

Fault Tolerance: Clustering introduces redundancy in the network by having multiple cluster heads. When a specific cluster head node reaches everybody-breakdown state, some other node within the cluster can run for the head leaving the network much more secure than in the initial automation system [53].

Localized Coordination and Communication: Clustering facilitates localized coordination and communication within each cluster, reducing the overhead and complexity of network-wide coordination [54]. Cluster heads can manage their respective clusters independently, making decisions and coordinating activities within their clusters.

Quality of Service (QoS) Support: Clustering can be leveraged to support different QoS requirements, including latency, throughput, and reliability, by employing different clustering strategies and protocols tailored to specific application needs [55].

3.1. Challenges and Constraints in Clustering

Clustering in WSNs faces several challenges and constraints that need to be addressed for efficient implementation and operation. Here are several important challenges and constraints associated with clustering in WSNs:

Energy Constraints: Sensor nodes have limited energy resources, typically powered by non-rechargeable batteries. Clustering algorithms and protocols need to be energy-efficient to prolong network lifetime [56]. The role of cluster heads can be energy-intensive due to additional responsibilities, like data aggregation and inter-cluster communication [57].

Cluster Head Selection: Selecting appropriate cluster heads is crucial for efficient clustering and network performance [58]. The criteria for cluster head selection may include factors like residual energy, node centrality, mobility, and communication capabilities. Improper cluster head selection can lead to unbalanced energy consumption, network partitioning, and reduced lifetime [59].

Cluster Formation and Maintenance: Cluster formation and maintenance processes can introduce additional overhead and complexity. Dynamic network conditions, such as node mobility, node failures, and changing network topology, can necessitate frequent cluster reorganization [60].

Inter-cluster and Intra-cluster Communication: Efficient intra-cluster communication is needed for data aggregation and coordination within a cluster. Inter-cluster communication is required for data forwarding and coordination between different clusters or with the sink node [61]. Routing protocols and medium access control (MAC) mechanisms need to be optimized both intra- and inter-cluster communication [62].

Data Aggregation and Fusion**:** Cluster heads are in control of data aggregation and fusion from their cluster members. Effective data gathering and integration techniques are required to reduce redundant data and conserve energy and bandwidth resources. Trade-offs may exist between energy efficiency and data accuracy, requiring careful consideration [63].

Scalability: As the network size and density increase, clustering mechanisms need to be scalable to handle larger networks efficiently. Scalability challenges may arise in terms of cluster formation, maintenance, routing, and resource management.

Quality of Service (QoS) Requirements: Different applications may have varying QoS requirements, such as latency, throughput, and reliability. Clustering protocols and strategies need to be tailored to meet specific QoS requirements, which can introduce additional complexity [64].

Node Mobility and Heterogeneity: In scenarios with mobile sensor nodes or heterogeneous node capabilities, clustering mechanisms need to adapt to dynamic network topologies and diverse node characteristics. Handling node mobility and heterogeneity can increase the complexity of cluster formation, maintenance, and load balancing [65].

Security and Privacy Concerns: Clustering can introduce new security vulnerabilities, such as compromised cluster heads or malicious node behavior. Secure clustering protocols and mechanisms are required to ensure data confidentiality, integrity, and authentication [66].

Trade-offs and Optimization Objectives: Clustering often involves trade-offs between various objectives, that includes energy efficiency, network lifespan, reliability of data, and QoS requirements. Optimization objectives may conflict with each other, requiring careful consideration and prioritization based on application requirements [67].

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Addressing these challenges and constraints requires innovative solutions at various levels, including clustering algorithms, communication protocols, data processing techniques, and network architectures.

4. CLUSTERING STRATEGIES IN WSNS

Clustering strategies in WSNs play a significant role in improving and optimizing network performance, energy efficiency, and overall lifetime [68]. These strategies able to broadly categorize according to different criteria, as objectives, methodologies, and network characteristics. Here are some commonly used clustering strategies in WSNs:

4.1. Centralized Clustering

Centralized clustering is an approach where a central authority or a designated node, typically the sink node and base station, is in charge for making clustering decisions and forming clusters in a WSN [69]. In this approach, the central authority collects information about the entire network, such as node locations, residual energy levels, and connectivity information, and then determines the optimal cluster formation based on a specific clustering algorithm or objective function.

4.2. Distributed Clustering

Distributed clustering is an approach in WSNs where sensor nodes collaborate with their neighbors to form clusters in a distributed manner, without relying on a central authority [70]. In this approach, each node makes clustering decisions based on local information, such as neighboring node locations, residual energy levels, and connectivity information [71]. In practice, hybrid approaches that combine elements of both centralized and distributed clustering may also be employed to balance the trade-offs and leverage the advantages of both approaches based on the specific application requirements and network characteristics. Comparison between Centralized and Distributed clustering shown in the Table 1.

Table 1 Centralized vs Distributed Clustering

Attributes	Centralized Clustering	Distributed Clustering
Control Entity	Single central controller (e.g., Base Station)	Distributed decision-making by autonomous nodes
Network Information	Global network information accessible to central entity	Nodes have limited local knowledge (neighbour nodes, energy levels)
Resource Allocation	Optimized resource allocation centrally managed	Resource allocation managed autonomously by nodes
Scalability	May face scalability challenges with network growth	Offers scalability and adaptability to dynamic network conditions
Fault Tolerance	Vulnerable to single point of failure (central entity)	Resilient to node failures; nodes can adaptively reconfigure
Complexity	Higher complexity due to centralized control and coordination	Lower complexity with distributed decision-making
Energy Efficiency	May optimize energy efficiency with global optimization	Efficient resource utilization through local decision-making

4.3. Hierarchical Clustering

Hierarchical clustering is a popular approach in WSNs where sensor nodes are organized into a multi-level hierarchical structure [72].

In this architecture, nodes are grouped into clusters, and these clusters are further grouped into higher order clusters, forming a tree shape hierarchy. At the top of the hierarchy is the sink node or base station [73].

4.4. Flat Clustering

Flat clustering, also known as non-hierarchical clustering, is an important technique used in WSNs to organize sensor nodes into groups or clusters based on certain criteria without imposing a hierarchical structure [74]. Unlike hierarchical clustering, where nodes are organized into nested clusters with multiple levels, flat clustering involves forming clusters of nodes at a single level, with no explicit hierarchy among clusters [75]. Comparison between Hierarchical Clustering and Flat Clustering shown in the Table 2.

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Table 2 Hierarchical vs Flat Clustering

Attributes	Hierarchical Clustering	Flat Clustering
Cluster Structure	Organizes nodes into nested hierarchical levels	Forms clusters at a single level, no hierarchy
Cluster Formation	Nodes are grouped into multiple levels (e.g., super-nodes, sub-clusters) based on specific criteria	Nodes form clusters independently based on local criteria
Cluster Head Selection	Cluster heads are selected at different levels of hierarchy, often based on global optimization criteria	Cluster heads are elected locally based on local information (e.g., proximity, energy level)
Data Aggregation	Hierarchical structure facilitates hierarchical data aggregation from leaf nodes to the root	Data aggregation occurs within each flat cluster before transmission to the base station
Scalability	May face scalability challenges with increasing network size due to hierarchical complexity	Generally scalable with simpler structure and decentralized control
Complexity	More complex due to hierarchical organization and centralized control	Less complex with flat organization and decentralized decision-making
Energy Efficiency	Hierarchical clustering can optimize energy efficiency with centralized control	Flat clustering conserve energy by reducing long distance transmissions

4.5. Static Clustering

Static clustering in WSNs provides a straightforward and efficient approach for organizing sensor nodes, particularly in stable and predictable environments. While it offers simplicity and reduced overhead, it also comes with limitations in terms of adaptability and energy balance. In static clustering, the roles of cluster heads and cluster members are assigned during the initial deployment phase and do not change unless a node fails or runs out of energy [76].

4.6. Dynamic Clustering

Dynamic clustering in WSNs involves the continuous adaptation of cluster formation and cluster head selection in response to changing network conditions [77]. In dynamic clustering, cluster heads and cluster memberships can be periodically updated or reorganized based on specific criteria or algorithms [78]. Comparison between static clustering and dynamic clustering shown in the Table 3.

Table 3 Static Clustering vs Dynamic Clustering

Attributes	Static Clustering	Dynamic Clustering
Cluster Formation	Formed once during network setup and remain fixed	Formed and reformed periodically based on network conditions
Cluster Head Selection	Chosen during network planning or initial deployment	Periodically re-elected or selected based on specific criteria
Adaptability	Cannot adapt to changes in network conditions or topology	Adapts to changing network topology, node failures, or energy depletion
Load Balancing	Limited, as cluster heads are fixed	Achieves better load balancing by rotating cluster head roles
Complexity	Simple implementation and maintenance	More complex algorithms and protocols for dynamic clustering

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Energy Efficiency	Uneven energy consumption, as cluster heads cannot be rotated	Better energy efficiency by distributing cluster head roles
Network Lifetime	May be shorter due to uneven energy depletion	Potentially longer by adapting to node failures and energy depletion

5. RECENT ADVANCES IN CLUSTERING STRATEGIES

Current trends in the clustering in WSNs are stated to be enhancing the energy efficiency of the network, the scalability and flexibility when employing different scenarios and embracing diverse technologies and that of employing new technologies such as machine learning and IoT. Here are some of the notable advances:

5.1. Energy-Efficient Clustering Algorithms

Energy-Efficient LEACH(EE-LEACH): These are improved algorithms of the Low-Energy Adaptive Clustering Hierarchy algorithm including the EE-LEACH, optimize the choice of cluster heads according to remaining energy, distance lifetime [79].

Hybrid Energy-Efficient Distributed (HEED): HEED enhances LEACH through utilizing residual energy and communication cost as primary metrics for cluster head selection, achieving better energy distribution and prolonged network operation[80].

5.2. Machine Learning Based Clustering

Reinforcement Learning: Algorithms using reinforcement learning (RL) adaptively select cluster heads and optimize clustering processes by learning from network conditions and performance metrics over time [81]. Specifically, RL is useful in dynamic environments, especially with respect to network topology.

Fuzzy Logic: Fuzzy logic type clustering algorithms handle the uncertainty and imprecision in WSN environments by considering multiple criteria such as node energy, mobility, and signal strength to make more nuanced clustering decisions [82].

K means Clustering: K means clustering is a prominent approach of clustering in the WSN. This method is mostly concerned with the Euclidean distance between nodes and the choosing of cluster heads according to the remaining of nodes energy [83]. First, the sink node receives information on the identity, location, and remaining energy of every node in the network.

Then, using the K means algorithm, the sink node clusters the sensors by computing the difference between each sensor node and the existing cluster centroids. then updates the cluster centroids depending on the average position of the nodes in every cluster [84].

5.3. Mobility Aware Clustering

Mobile Node Adaptation: Strategies that incorporate node mobility information into clustering decisions help maintain stable clusters and reduce the frequency of re-clustering in networks with mobile nodes, such as in vehicular sensor networks [85].

Trajectory-Based Clustering: This approach predicts the future positions of mobile nodes and forms clusters that minimize the movement of nodes between clusters, thereby reducing re-clustering overhead [86].

5.4. Hierarchical and Multi-Level Clustering

Multi-Tier Clustering: Multi-level clustering strategies involve organizing nodes into multiple hierarchical levels, where higher-level clusters manage and coordinate lower-level clusters. This approach improves scalability and reduces communication overhead [87].

Zone-Based Clustering: This technique splits the network in zones, each controlled by a zone leader. Within each zone, standard clustering algorithms are applied, balancing the load and improving the manageability of large-scale networks [88].

5.5. Bio-Inspired Clustering Algorithms

Swarm Intelligence: Algorithms inspired by natural phenomena, such as ant colony optimization (ACO) and particle swarm optimization (PSO), dynamically adjust capacity to handle complex optimization issue, adapt to dynamic environments and provide near-optimal solutions. These clustering are based on local node interactions, mimicking the behavior of social insects [89].

Genetic Algorithms: GAs evolve optimal clustering configurations over generations by simulating the process of natural selection, improving energy efficiency and network lifetime through iterative optimization [90].

5.6. Security-Aware Clustering

Secure Clustering Protocols: Recent advancements address security concerns by incorporating authentication, encryption, and intrusion detection mechanisms into clustering protocols, ensuring secure communication within clusters [91].

Blockchain-Based Clustering: Utilizing blockchain technology to create secure, tamper-proof records of clustering decisions and data transmissions, enhancing trust and integrity in WSNs [92]. These recent advances in clustering strategies for WSNs seek to resolve the evolving issues of energy efficiency, scalability, adaptability, security,

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and QoS, leveraging new technologies and interdisciplinary approaches to enhance the overall performance and longevity of sensor networks.

6. COMPARISON OF CLUSTERING ALGORITHMS

Table 4 presents an extensive overview of various algorithms used for optimization of clustering in WSNs. It covers a wide range of approaches, including distributed, centralized, probabilistic, weight-based, metaheuristic, fuzzy logic, and partitioning-based algorithms. Each algorithm is evaluated based on its objective, advantages, disadvantages, and relevant references from recent years (after 2020). The table highlights the trade-offs and considerations for each algorithm, such as energy efficiency, network lifetime, computational complexity, convergence speed, adaptability to dynamic environments, and handling of uncertainties and constraints.

Table 4 Comparison of Clustering Optimization Algorithms

Algorithm	Approach	Objective	Advantage	Disadvantage
LEACH (Low-Energy Adaptive-Clustering Hierarchy) [93]	Distributed, Probabilistic	Reduce the quantity of energy use by rotating cluster head	Simple, efficient, proven	Static clustering, not suitable for dynamic environments
HEED (Hybrid Energy-Efficient Distributed Clustering) [94]	Distributed, Hybrid	Maximize network lifetime by efficient cluster head selection	More efficient than LEACH, considers residual energy	Complex, overhead for frequent re-clustering
DWEHC (Distributed Weight-based Energy-efficient Hierarchical Clustering) [95]	Distributed, Weight-based	Maximize network lifespan by managing energy usage	Considers multiple factors like energy, centrality, and density	Overhead for weight calculations and cluster formation
EEHCT (Energy-Efficient Hybrid Clustering Technique) [96]	Distributed, Competition-based	Minimize energy consumption for non-cluster head nodes	Reduces overheads for non-cluster heads	Fixed cluster formation, not suitable for dynamic topologies
EMUC (Energy Efficient Multi-hop routing with Unequal Clustering) [97]	Centralized, Unequal clustering	Minimize energy consumption by unequal cluster sizes	Efficient for multi-hop communication	Centralized approach, requires global knowledge
PSO (Particle Swarm Optimization) [98]	Metaheuristic	Optimize cluster formation and routing for energy efficiency	Adaptive, flexible, can handle complex scenarios	Convergence issues, parameter tuning required
GA (Genetic Algorithm) [99]	Metaheuristic	Optimize cluster head selection and route for energy efficiency	Robust, can handle complex constraints	Computationally expensive, premature convergence
ACO (Ant Colony Optimization) [100]	Metaheuristic	Optimize cluster formation and data routing for energy efficiency	Distributed, self-organizing, robust	Slow convergence, parameter tuning required
Fuzzy [101]	Fuzzy Logic	Optimize cluster	Can handle	Complex rule design,

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		head selection based on fuzzy rules	uncertainty, imprecision	computational overhead
K-Means [102]	Partitioning	Optimize cluster formation by minimizing intra-cluster distances	Simple, efficient, widely used	Sensitive to initialization, outliers
Improved K-means [103]	Enhanced version	Optimize initial centroids and dynamic adjustments	Better clustering stability, reduces sensitivity to initial conditions	Higher computational overhead compared to basic K-means
FCM (Fuzzy C Means) [104]	Fuzzy Partitioning	Optimize cluster formation using fuzzy membership	Handles uncertainty, overlapping clusters	Complex membership calculations
EM (Expectation-Maximization) [105]	Probabilistic	Optimize cluster formation based on maximum likelihood	Handles uncertainty, Soft clustering	Sensitive to initialization, computational complexity
SA (Simulated Annealing) [106]	Metaheuristic	Optimize the path of sink node and cluster formation	Robust, can escape local optima	Slow convergence
FA (Firefly Algorithm) [107]	Metaheuristic	Optimize cluster formation and cluster head selection	Flexible, can handle complex scenarios	Sensitive to parameter settings.
ABC (Artificial Bee Colony) [108]	Swarm intelligence	Optimize cluster formation and routing for energy efficiency	Easy to implement, self-organizing, robust	Can be slow to convergence for large problem sizes
CS (Cuckoo Search) [109]	Metaheuristic	Optimize range of node and reduce redundancy	Robust, can handle complex constraints	Premature convergence, parameter tuning required

7. RESULTS AND DISCUSSIONS

Considering the data presented in table 4, it is evident that there is not a solution that works for every clustering optimization in WSNs. The selection of the optimum algorithm calls for various considerations, which include the characteristics of the network in question, optimization goals to be achieved, and available computational capacity, as well as requirements towards convergence. However, some algorithms stand out as more promising or widely adopted: Sorts of metaheuristic algorithms for example PSO, GA, ACO and SA have received much attention due to their capability of dealing with tough optimization problem, operation in dynamic condition and ability to find near optimal solution. Hence, most of the previous algorithms as LEACH (Low-Energy Adaptive- Clustering Hierarchy) and its derivatives are still prevalent and are used as references because they are simple, effective, and have demonstrated energy saving

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capability. Fuzzy logic-based algorithms, such as Fuzzy C-Means (FCM), are well-suited for WSNs as they can handle uncertainty and imprecision in data and sensor measurements. There are other types of algorithms that can be used in WSNs, namely fuzzy logic-based algorithms due to their capability of dealing with vague and imprecise information and sensor measurements typically found in WSNs as FCM. The combination of different techniques like fuzzy with metaheuristic algorithms or clustering with routing optimization provides better solutions as it covers different objectives and advantages of involved techniques in a single solution. Therefore, criteria for choosing the best algorithm include meeting the specific WSN scenario, optimizing goals, computational resources, and optimal balance between performance, energy consumption, and duration to convergence. Hence, specificity of performance comparisons and metrics under different network conditions is paramount in determining the best algorithm for typical WSN uses. Moreover, the invention of new algorithms or change of existing algorithm is a process in progress, which indicates constant research of cluster optimization for WSNs.

8. FUTURE WORK AND CHALLENGES

The study of clustering approaches for WSNs has obtained remarkable developments over the recent years; however, it is also evident that some issues remain open and promising research topics for further advancements can be detected. Future research in clustering strategies for WSNs should concentrate on implementing new and innovative technologies to enhance the capabilities and performance of these networks. Another noticeable avenue is the interaction with other systems such as the fifth-generation mobile network, internet of things, and the edge computing systems. Thus, it is possible to integrate the features of these technologies to build more effective WSN solutions. It is also possible to invent adaptive clustering algorithms applying AI and machine learning that operate well under different network conditions; at the same time, there is a need for the invention of newer and more secure protocols using blockchain and other forms of advanced cryptography due to the increasing security threats. Such research directions are promising; however, several issues must be considered for proper management. Another task preventing WSNs from achieving high efficiency is the quest for scalability with WSNs' size and the density of nodes; Other inherently complex issues include heterogeneity in terms of node functionality and the capability to manage the distributed resources available. Another problem is associated with a possibility of node mobility or possible changes of the network topology and the need to implement adaptations in real time while meeting the constraints in energy consumption as well as in real time data processing. When testing the new clustering strategies, their ability to increase performance should be proved in real-world large-scale trials and experiments. This would assist in identifying real life implementation issues that may be hard to define in simulations or in mini tests that do not represent the real-world scenario which should make the solutions provided, versatile enough to deal with the real world issues.

9. CONCLUSION

These algorithms are widely used and known to be efficient; nevertheless, the effectiveness of some of them may vary depending on the particular WSN scenario, its size, node density, and certain optimization objectives. Therefore, other factors such as computational complexity, the convergence of the algorithm, and the amount of energy to be used during the calculation should be considered while deciding on the type of algorithm best suited for use in a WSN. To make suitable decisions, researchers and developers need to analyze these factors before using an algorithm on a WSN to achieve the best results. Further, testing the system in real life and using case simulation can be very helpful in analyzing the behavior of the designed algorithm. Moreover, it is crucial to understand the dynamic character of the environment in which WSNs operate. Factors as node failures, varying network conditions, and environmental interferences can significantly affect the performance of clustering algorithms. Thus, adaptability and robustness become key attributes for algorithms to ensure their effectiveness in real-world applications. Another consideration is the balance between algorithm complexity and energy consumption, while sophisticated algorithms may provide more accurate clustering or better load balancing, they often demand more computational power, which is not practical for resource-constrained sensor nodes. In addition, leveraging hybrid approaches that blend the advantages of different algorithms could offer promising results for specific WSN scenarios, particularly those requiring a trade-off between performance metrics like energy efficiency, scalability, and reliability. Continuous research and innovation in clustering algorithms, as well as advancements in hardware, could further improve the overall functionality and lifespan of WSNs. Considering all these factors, it is achievable to select the appropriate algorithm and method that would be fit for the WSNs application and provide the required performance outcome. By ensuring a thorough evaluation of both the algorithm's theoretical aspects and its practical implementation, researchers can design more robust, scalable, and energy-efficient systems, ultimately improving the dependability and durability of WSN in diverse ways of application.

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