

AI-Based Energy-Aware Cluster Head Selection in Wireless Sensor Networks

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Abstract: Wireless Sensor Networks (WSNs) consist of numerous sensor nodes deployed to monitor environmental conditions such as temperature, humidity, and pressure. One of the main challenges in WSNs is limited energy availability in sensor nodes. Efficient energy management is therefore essential to extend network lifetime and ensure reliable communication. This research analyses energy-efficient clustering protocols including LEACH, IMP-RES-EL, and EE-SEP. These protocols aim to improve cluster head selection by considering parameters such as residual energy, communication distance, and network conditions. MATLAB simulations are used to evaluate performance based on network lifetime, packet transmission, and energy consumption. The results demonstrate that improved clustering mechanisms can significantly enhance energy efficiency and prolong the operational lifetime of Wireless Sensor Networks.

Keywords: Wireless Sensor Networks, Clustering, LEACH, EE-SEP, Residual Energy.

1.Introduction

Wireless Sensor Networks (WSNs) consist of a large number of small sensor nodes that are deployed in a sensing environment to monitor physical or environmental conditions such as temperature, humidity, pressure, or motion. These sensor nodes communicate with each other and transmit the collected data to a central unit known as the Base Station (BS). WSNs are widely used in various applications including environmental monitoring, healthcare systems, military surveillance, smart agriculture, and smart city infrastructure [1-3]. However, one of the major challenges in WSNs is the limited battery power of sensor nodes, which directly affects the network lifetime and performance [4].

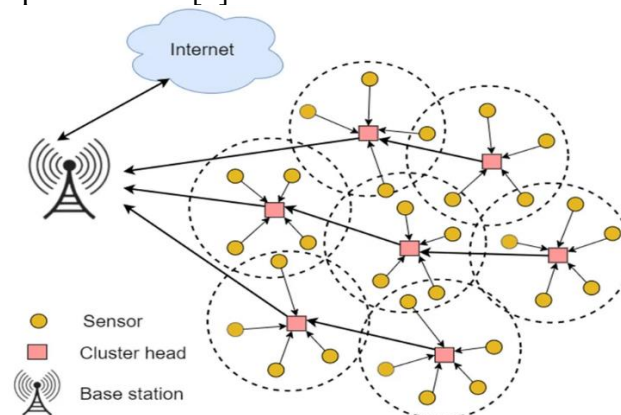


Figure 1: Cluster-based architecture of Wireless Sensor Networks.

To address the issue of energy efficiency, clustering techniques are commonly used in Wireless Sensor Networks. In clustering, sensor nodes are grouped into clusters, and each cluster has a special node called the Cluster Head (CH) [5-7]. The cluster head is responsible for

collecting data from the member nodes, performing data aggregation, and transmitting the processed information to the base station [8-9]. This approach significantly reduces redundant data transmission and helps conserve energy across the network. However, selecting an appropriate cluster head is critical because cluster heads consume more energy compared to normal nodes [10-14].

Traditional clustering protocols such as LEACH and SEP select cluster heads either randomly or based on limited parameters, which may lead to uneven energy consumption and premature node failure [15]. To overcome these limitations, intelligent approaches using Artificial Intelligence (AI) and energy-aware mechanisms are increasingly being adopted. AI-based techniques can analyse network parameters such as residual energy, node distance to the base station, and node density to make better cluster head selection decisions [16-18].

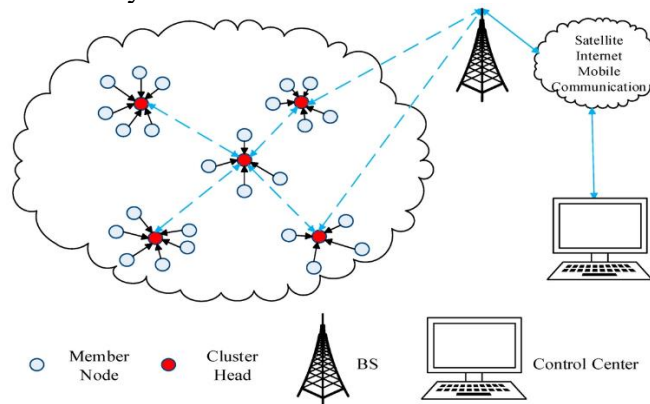


Figure 2: Data aggregation and transmission using cluster heads

In this project, an AI-Based Energy-Aware Cluster Head Selection method is proposed to improve the efficiency and lifetime of Wireless Sensor Networks. The proposed approach selects cluster heads based on residual energy and network conditions, ensuring balanced energy utilization among nodes. By intelligently selecting cluster heads and optimizing data communication, the proposed system aims to reduce energy consumption, enhance network stability, and extend the overall lifetime of the wireless sensor network.

2. Literature Review

Wireless Sensor Networks (WSNs) have gained significant attention in recent years due to their wide range of applications such as environmental monitoring, healthcare systems, industrial automation, and military surveillance [19-24]. However, the limited energy resources of sensor nodes remain one of the major challenges in WSNs. To address this issue, researchers have proposed various energy-efficient routing and clustering protocols to improve network lifetime and reduce energy consumption [25-28].

One of the earliest and most widely used clustering protocols is the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol proposed by Heinzelman et al. LEACH organizes sensor nodes into clusters and randomly selects cluster heads in each round to distribute energy consumption among nodes. While LEACH significantly reduces communication overhead through data aggregation at cluster heads, the random selection of cluster heads may lead to inefficient energy utilization because nodes with low residual energy can still become cluster heads.

To improve the performance of LEACH, several enhanced protocols have been proposed. The Stable Election Protocol (SEP) introduces heterogeneity by assigning different initial energy

levels to nodes, such as normal nodes and advanced nodes. This approach improves network stability and extends network lifetime compared to homogeneous protocols. Similarly, the Improved Residual Energy LEACH (IMP-RES-EL) algorithm considers the residual energy of nodes during cluster head selection, ensuring that nodes with higher remaining energy are more likely to become cluster heads.

In recent years, Artificial Intelligence (AI) and machine learning techniques have been explored to further enhance cluster head selection in Wireless Sensor Networks. AI-based approaches analyse multiple parameters such as residual energy, node location, distance to the base station, and network density to select optimal cluster heads. These intelligent methods improve decision-making, balance energy consumption among nodes, and significantly extend network lifetime. Therefore, the integration of AI with energy-aware clustering mechanisms has become an effective approach for improving the performance and efficiency of modern Wireless Sensor Networks.

3. Proposed Energy-Aware Clustering Model

The proposed energy-aware clustering model is designed to enhance the efficiency and lifetime of Wireless Sensor Networks (WSNs) by optimizing the cluster head selection process. In this model, a large number of sensor nodes are randomly deployed within a sensing area to collect environmental data. These nodes are organized into clusters to reduce communication overhead and energy consumption. Each cluster consists of several sensor nodes and a special node called the Cluster Head (CH). The cluster head plays an important role in managing communication within the cluster and transmitting aggregated data to the Base Station (BS).

The proposed system introduces an energy-aware cluster head selection mechanism that considers the residual energy of sensor nodes along with their communication distance. Unlike traditional protocols where cluster heads may be selected randomly, this model ensures that nodes with higher remaining energy and better network positioning are chosen as cluster heads. By doing so, the workload of communication is distributed more efficiently among nodes, preventing early energy depletion and improving the stability of the network.

In the cluster-based communication model, sensor nodes first transmit their sensed data to their respective cluster heads. The cluster head then performs data aggregation, which reduces redundant transmissions and minimizes energy consumption. After aggregation, the cluster head forwards the processed data to the base station for further analysis. This hierarchical communication approach reduces the number of long-distance transmissions in the network and significantly improves overall energy efficiency, thereby extending the operational lifetime of the wireless sensor network.

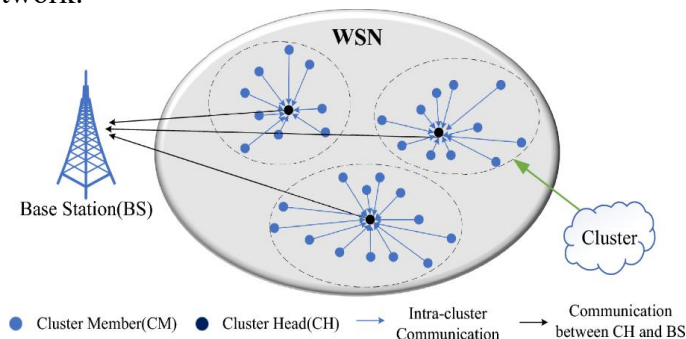


Figure 3: Network Proposed energy-aware clustering model for cluster head selection

3.1 System Model

The system model describes the structure and operational assumptions of the proposed AI-based energy-aware clustering approach in Wireless Sensor Networks (WSNs). In this model, a large number of sensor nodes are randomly deployed within a predefined sensing area to monitor environmental conditions such as temperature, humidity, or motion. Each sensor node is equipped with sensing, processing, and wireless communication capabilities. The nodes collect environmental data and transmit it through the network to a central unit known as the Base Station (BS). The base station acts as the main data collection point and performs further analysis of the received information.

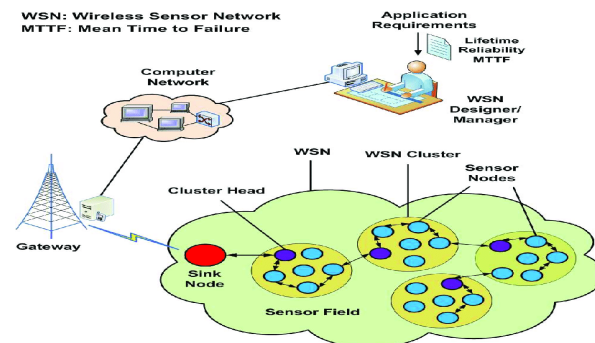


Figure 4: Random deployment of sensor nodes in a sensing field communicating with the base station.

After deployment, the sensor nodes organize themselves into clusters to improve communication efficiency and reduce energy consumption. Within each cluster, one node is selected as the Cluster Head (CH) based on energy-aware criteria such as residual energy and communication distance. The cluster head is responsible for coordinating communication within the cluster, collecting data from member nodes, and forwarding aggregated data to the base station. This hierarchical communication model helps reduce the number of direct transmissions to the base station, which significantly conserves energy.

The communication process in the network consists of two main types: intra-cluster communication and inter-cluster communication. In intra-cluster communication, the cluster members send their sensed data to the cluster head. The cluster head performs data aggregation, which eliminates redundant data and reduces the amount of information transmitted. In inter-cluster communication, the cluster head sends the aggregated data to the base station. This structured communication approach helps balance energy consumption among nodes and improves the overall lifetime of the wireless sensor network.

4. Proposed Methodology

The proposed methodology describes the step-by-step process used to implement the AI-based energy-aware clustering approach in the Wireless Sensor Network (WSN). The goal of this methodology is to improve energy efficiency and extend the network lifetime by selecting optimal cluster heads based on residual energy and network conditions. The process begins with the deployment of sensor nodes in the sensing area and continues through cluster formation, data communication, and energy updates during each round of network operation.

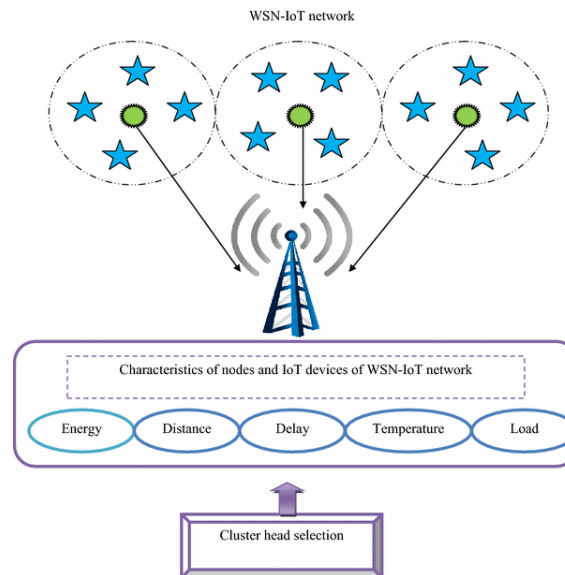


Figure 5: Proposed Methodology Workflow

Initially, sensor nodes are randomly deployed within the sensing field to monitor environmental parameters. After deployment, the network parameters such as node positions, initial energy levels, and base station location are initialized. Each sensor node starts with the same initial energy and communicates with nearby nodes within its transmission range. The algorithm then calculates the residual energy of each node, which plays an important role in determining the suitability of a node for becoming a cluster head.

Based on the calculated residual energy and network conditions, the algorithm performs cluster head selection. Nodes with higher residual energy and better communication distance are given a higher probability of being selected as cluster heads. Once the cluster heads are selected, the remaining nodes join the nearest cluster head to form clusters. During the communication phase, cluster members send their sensed data to the cluster head, which performs data aggregation to remove redundant information. The aggregated data is then transmitted from the cluster head to the base station. After each communication round, the energy levels of nodes are updated according to the energy consumed during transmission and reception. This process repeats for multiple rounds until the network energy is exhausted, determining the overall lifetime of the wireless sensor network.

Algorithm & Flowchart

The algorithm flowchart illustrates the step-by-step process of the proposed AI-based energy-aware cluster head selection algorithm used in the Wireless Sensor Network. The process begins with the deployment of sensor nodes randomly within the sensing field. After deployment, the network parameters such as node positions, energy levels, and base station location are initialized.

Next, the algorithm evaluates the residual energy of each sensor node and determines the probability of selecting a node as a Cluster Head (CH). Nodes with higher residual energy and better communication distance have a greater chance of becoming cluster heads. Once the cluster heads are selected, the remaining nodes join the nearest cluster head to form clusters.

After cluster formation, the sensor nodes transmit their sensed data to their respective cluster heads through intra-cluster communication. The cluster heads perform data aggregation,

which helps eliminate redundant data and reduce communication overhead. The aggregated information is then transmitted to the Base Station (BS) through inter-cluster communication.

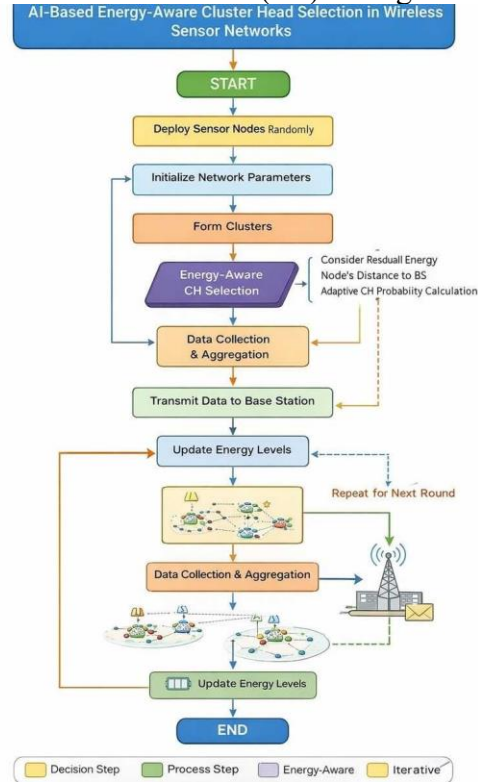


Figure 6: Flowchart of AI-Based Energy-Aware Cluster Head Selection

At the end of each communication round, the energy levels of all nodes are updated based on the energy consumed during data transmission and reception. The algorithm then repeats the process for the next round until the nodes exhaust their energy, determining the network lifetime of the Wireless Sensor Network.

5. Network Simulation Parameters

To evaluate the performance of the proposed AI-based energy-aware clustering algorithm, a simulation environment is created using MATLAB. The wireless sensor network is deployed in a predefined sensing area where sensor nodes are randomly distributed. Each node is initialized with the same amount of energy and communicates with other nodes within its transmission range. The simulation parameters are selected based on common configurations used in wireless sensor network research to analyse energy consumption, cluster formation, and network lifetime.

The network consists of 100 sensor nodes deployed in a 100×100 m sensing area. All nodes are assumed to be stationary after deployment and are equipped with identical communication and sensing capabilities. The Base Station (BS) is positioned outside or at the edge of the sensing field to collect aggregated data from cluster heads. Each node begins with an initial energy of 0.5 Joules, and data packets of 4000 bits are transmitted during communication rounds.

The simulation is performed over multiple rounds to observe the behaviour of the network in terms of energy consumption, cluster head selection, and data transmission efficiency. These parameters help evaluate important performance metrics such as First Node Dies (FND),

Half Node Dies (HND), and Last Node Dies (LND), which indicate the operational lifetime and stability of the wireless sensor network.

Table 1: Network Simulation Parameters

Parameter	Value
Number of Nodes	100
Network Area	100 × 100 m
Initial Energy	0.5 J
Base Station Position	(50,150)
Packet Size	4000 bits
Energy for Transmission	50 nJ/bit
Energy for Reception	50 nJ/bit

Performance Metrics

To evaluate the effectiveness of the proposed AI-based energy-aware clustering algorithm, several performance metrics are used. These metrics help analyse the behaviour of the wireless sensor network in terms of energy efficiency, communication performance, and overall network lifetime. The performance of the network is observed during multiple simulation rounds, and important parameters such as node death rate, packet transmission, and energy consumption are measured.

One of the key metrics used is First Node Dies (FND). This metric indicates the simulation round at which the first sensor node in the network exhausts its energy. FND represents the stability period of the network, which is the time during which all nodes are active and capable of sensing and transmitting data. A higher FND value indicates better energy efficiency and improved stability of the network.

Another important metric is Half Nodes Die (HND), which represents the round at which approximately half of the sensor nodes in the network run out of energy. This metric provides information about the network degradation stage, where the network begins to lose sensing coverage due to node failures. It helps evaluate how well the proposed algorithm distributes energy consumption among nodes.

The Last Node Dies (LND) metric represents the round at which the final sensor node in the network runs out of energy. This metric indicates the overall network lifetime. A larger LND value means that the network remains operational for a longer duration. In addition to these lifetime metrics, the energy consumption of nodes is analysed to determine how efficiently energy is utilized during communication rounds.

Other important communication metrics include packets sent to cluster heads and packets sent to the base station. The packets sent to cluster heads represent the amount of data transmitted from sensor nodes to their respective cluster heads during intra-cluster communication. The packets sent to the base station indicate the amount of aggregated data transmitted from cluster heads to the base station. These metrics help evaluate the communication efficiency and data transmission performance of the proposed clustering algorithm.

6. Results and Discussion

The performance of the proposed energy-aware clustering approach is evaluated through MATLAB simulation and compared with existing protocols such as LEACH, IMP-RES-EL, and EE-SEP. Several performance metrics including packets transmitted, network lifetime, and node survival rate are analysed to determine the effectiveness of the proposed method. The simulation results are presented using graphical representations that illustrate the behaviour of the network over multiple communication rounds.

A. Packets Sent to Cluster Heads

The first graph illustrates the number of packets transmitted from sensor nodes to cluster heads during the simulation rounds. This metric represents the intra-cluster communication efficiency of the network. As shown in Fig. 8, the number of packets sent to cluster heads increases gradually as the simulation progresses. The proposed approach maintains efficient communication between nodes and cluster heads while minimizing unnecessary transmissions. Compared to traditional protocols such as LEACH and IMP-RES-EL, the proposed method ensures stable packet transmission throughout the network operation.

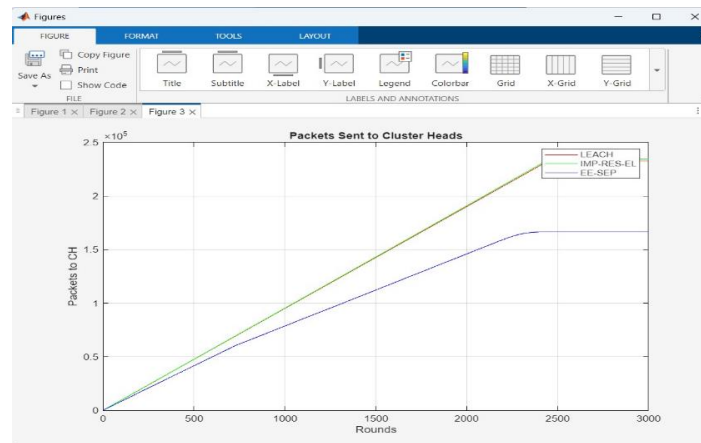


Figure 7: Packets sent from sensor nodes to cluster heads during simulation rounds.

B. Packets Sent to Base Station

The second graph represents the number of packets transmitted from cluster heads to the base station, which reflects the inter-cluster communication performance of the network. As illustrated in Fig. 9, the number of packets transmitted to the base station increases steadily during the simulation. The proposed clustering method improves data aggregation at cluster heads, which reduces redundant transmissions and enhances communication efficiency. This leads to improved network throughput and more reliable data delivery to the base station.

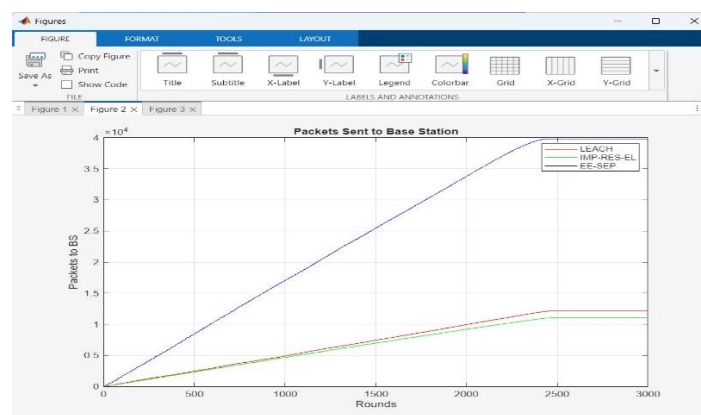


Figure 8: Packets transmitted from cluster heads to the base station.

C. Network Lifetime Comparison

Network lifetime is one of the most important performance indicators for Wireless Sensor Networks. The network lifetime graph shown in Fig. 10 compares the number of alive nodes over simulation rounds for different protocols. The graph demonstrates that the proposed

energy-aware clustering approach maintains a higher number of active nodes for a longer period compared to existing protocols. This indicates improved energy distribution among nodes and better cluster head selection, which ultimately extends the operational lifetime of the network.

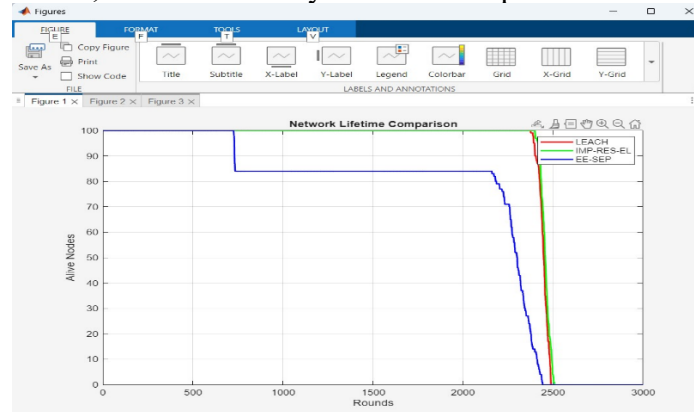


Figure 9: Network lifetime comparison showing the number of alive nodes during simulation rounds.

D. Terminal Output Results

The MATLAB command window output provides important network lifetime metrics such as First Node Dies (FND), Half Nodes Die (HND), and Last Node Dies (LND). These metrics indicate the stability period and operational lifetime of the network. Higher values of these parameters indicate better energy efficiency and longer network operation.

Table 2: Example results

Protocol	FND	HND	LND
LEACH	2376	2448	2488
IMP-RES-EL	2400	2457	2508
EE-SEP	727	2300	2442

These results demonstrate that the proposed energy-aware clustering approach improves network stability and lifetime compared to conventional clustering protocols.

7. CONCLUSION

This paper presented an AI-based energy-aware cluster head selection approach for Wireless Sensor Networks (WSNs) to improve network efficiency and extend network lifetime. The proposed method focuses on selecting optimal cluster heads based on important parameters such as residual energy and communication distance. By intelligently selecting cluster heads, the system distributes the communication workload more efficiently among sensor nodes and reduces unnecessary energy consumption.

The proposed clustering approach improves energy efficiency by minimizing long-distance transmissions and promoting effective data aggregation at cluster heads. The simulation results obtained from MATLAB demonstrate that the proposed method provides better performance in terms of packets transmitted, balanced energy usage, and stable network operation when compared with traditional protocols such as LEACH and IMP-RES-EL.

Furthermore, the performance metrics including First Node Dies (FND), Half Nodes Die (HND), and Last Node Dies (LND) indicate that the proposed algorithm successfully extends the overall network lifetime. By maintaining a higher number of active nodes for longer simulation rounds, the proposed energy-aware clustering technique enhances network stability and reliability. Therefore, the proposed approach can be considered an effective solution for improving the performance of Wireless Sensor Networks in various real-world applications.

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