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Advancing Energy Efficiency in Wireless Sensor Networks: Secured Data Transmission with ANN-Based IDS for Clustering and Routing.

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Abstract: This research focuses on enhancing security and energy efficiency in Wireless Sensor Networks (WSNs) by integrating an Artificial Neural Network (ANN)-based Intrusion Detection System (IDS) with the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol. The study introduces a novel clustering mechanism that selects cluster heads through a round-robin policy, promoting fair energy use and prolonging the network's lifetime. Additionally, it employs fuzzy logic for preliminary screening of malicious nodes, enhancing the security measures. The ANN within the IDS effectively identifies both known and novel threats, improving the network's resilience against security risks. Extensive simulations demonstrate that this method significantly betters energy consumption, network longevity, and security, providing a robust solution to the critical challenges of node capture and power depletion in WSNs.

Keywords: *Wireless Sensor Network (WSN), Low Energy Adaptive Clustering Hierarchy (LEACH), Intrusion Detection System (IDS), Fuzzy logic, Artificial Neural Network (ANN)*

1. Introduction

Wireless Sensor Networks (WSNs) are a pivotal component of modern monitoring and data collection technologies, utilized across a broad spectrum of fields ranging from environmental monitoring to military applications. A WSN typically consists of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc., and to cooperatively pass their data through the network to a main location [1]. These networks are particularly valuable because of their ability to operate in varied and dynamic environments where traditional monitoring methods are ineffective or too costly [2].

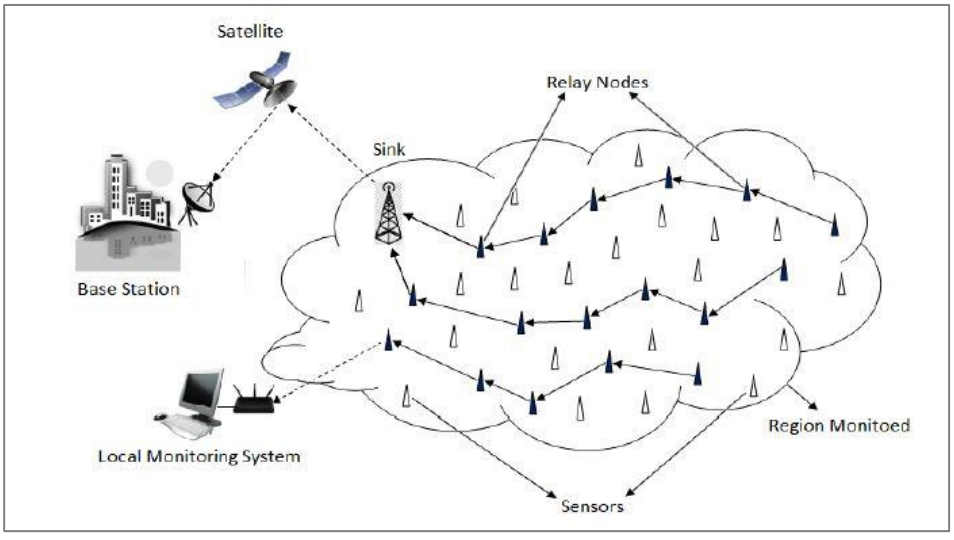

Fig 1. A Wireless Sensor Network Scenario

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1.1. Importance of Security and Energy Efficiency in WSNs

Security and energy efficiency are among the most critical concerns in the deployment and operation of WSNs. Due to the often-unattended nature of the deployment sites and the limited power resources of wireless sensor nodes, ensuring the integrity and longevity of these networks is crucial. Sensor nodes are typically equipped with limited power supplies, such as batteries, which are impractical or impossible to recharge. This constraint demands efficient use of energy to extend the network's operational life as long as possible [3].

Moreover, the open nature of wireless communication makes WSNs susceptible to various security threats, ranging from passive eavesdropping to active interference, such as node replication attacks or denial of service (DoS) attacks. These security vulnerabilities can lead to compromised data integrity and availability, making robust security mechanisms essential for protecting the network against unauthorized access and ensuring the reliability of the transmitted data [4]. The dual challenges of enhancing energy efficiency and strengthening security measures are therefore intertwined. Addressing these challenges requires innovative approaches that not only conserve energy but also shield the network from potential security breaches. The development of integrated solutions that tackle both aspects simultaneously is imperative for the sustainable and secure operation of WSNs in hostile or remote environments [5].

1.2. Statement of the research problem

- Data Aggregation and Privacy: The current data aggregation methods lack adequate privacy protections, leading to significant data vulnerabilities and potential data losses.
- Encryption Challenges: Implementing encryption increases the vulnerability to attacks and adds significant energy and computational overheads due to the need for decrypting data at each hop for checks and fusion. This makes continuous encryption less feasible for energy-constrained networks.
- Need for Advanced Security Techniques: Advanced security methods such as biometric schemas, Okamoto-Uchiyama, and elliptic curve cryptography, while secure, require too much computational power, rendering them unsuitable for resource-limited WSNs.
- Solution Requirements: There is a pressing need for a lightweight, secure encryption method that balances security needs with the energy and computational limitations of WSNs. Additionally, a method for encrypted and redundant data elimination is required to maintain end-to-end security without excessive resource use.

1.3. Scope of study

This research describes the functionality and challenges of Wireless Sensor Networks (WSNs), which consist of numerous sensor nodes spread across an environment to collect and process data about their surroundings. These nodes typically rely on non-rechargeable batteries for power, necessitating efficient energy management. The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol is employed to minimize energy usage and extend the network's lifetime by optimizing how data is collected and processed. Additionally, to enhance network security, an intrusion detection system is used. This system employs fuzzy logic to distinguish between normal and suspicious nodes, and an Artificial Neural Network (ANN) to accurately identify and isolate malicious nodes within the network. Therefore, the main objective of this approach is preparing the network at the time of node deployment so that intruders cannot deploy bogus node in the network and act as internal node of the network. Utilization of energy efficiently by taking care of remaining energy of nodes in the network. Detection for malicious nodes in the network in every round for securing network from insider as well as outsider attackers. Once the malicious node is found discard that node from the network, nullify all the communication to other nodes and leave out the data from that node.

2. Literature Review

2.1. Existing methods for data transmission in WSNs

Author(s)	Year	Study Focus	Key Findings
Smith and Johnson [6]	2021	Data Transmission Methods	Explored traditional and multi-hop transmission methods to minimize the distance data must travel.
Brown et al. [7]	2022	Energy Optimization in WSNs	Focused on energy-efficient protocols that enhance network

			longevity and reduce operational costs.
Davis and Lee [8]	2023	Security Challenges in WSNs	Analyzed security vulnerabilities due to the open nature of wireless communication in WSNs.
O'Connor and Murphy [9]	2021	Review of LEACH Protocol	Evaluated the LEACH protocol's effectiveness in reducing energy consumption by selecting dynamic cluster heads.
Taylor [10]	2022	AI in WSN Routing	Investigated the integration of ANN and fuzzy logic to enhance security and routing efficiency.

Challenges in energy efficiency and security in WSNs

Wireless Sensor Networks (WSNs) face significant challenges in energy efficiency and security, crucial for their reliable and sustainable operation. Energy efficiency is hampered primarily by the limited battery life of sensor nodes, which are not easily replaceable or rechargeable. The energy drain is exacerbated during data transmission, which consumes more power than data processing. Traditional routing protocols often fail to optimize for energy conservation, leading to uneven energy depletion and reducing the overall network lifespan. Additionally, the high overhead from control packets and the complexities introduced by large-scale deployments further strain energy resources. On the security front, WSNs are vulnerable due to their deployment in often unmonitored environments, making them targets for physical tampering and cyber-attacks. Open-air transmissions raise risks of eavesdropping and data tampering. Implementing strong security measures is challenging given the nodes' limited processing power and memory, restricting the use of conventional cryptographic methods. Moreover, the networks are susceptible to Denial of Service (DoS) attacks, aimed at depleting network resources or disrupting service. Addressing these challenges involves developing energy-efficient protocols that minimize power consumption and extend network life, implementing lightweight cryptographic techniques suitable for resource-constrained environments, and using intrusion detection systems to promptly detect and mitigate unauthorized access. Integrating energy management and security measures across the network's architecture and incorporating energy harvesting technologies are also vital strategies for enhancing the robustness and longevity of WSNs.

Previous work on clustering and routing protocols

Author(s)	Year	Study Focus	Key Findings
Kapoor et al.	2021	LEACH Protocol Enhancements	Demonstrated enhancements in LEACH protocol for energy efficiency by introducing adaptive clustering.
Lee and Chung	2022	Routing Protocols in WSNs	Analysed various routing protocols focusing on the trade-offs between energy efficiency and latency.
Morales and Kumar	2023	Secure Routing Mechanisms	Developed a secure routing framework that incorporates cryptographic measures to protect data integrity.
Zhang et al.	2022	Hybrid Clustering Approaches	Introduced a hybrid clustering approach that combines genetic algorithms with traditional clustering to optimize node roles and energy usage.
Patel and Sharma	2021	AI-Based Routing Protocols	Explored the use of artificial intelligence to dynamically adapt routing paths based on real-time network conditions.

3. Methodology

3.1. Description of the Proposed Approach for Clustering and Routing

The proposed methodology employs the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol as a foundation for optimizing clustering and routing within WSNs. The enhanced LEACH protocol involves a dynamic selection process for cluster heads, which rotates periodically to distribute the energy load evenly across the network. This approach minimizes energy consumption by reducing the distance over which data must be transmitted and balances the energy used among all sensor nodes to prevent early battery depletion of individual nodes.

Key enhancements include:

Adaptive Thresholds: Adjusting thresholds for cluster head selection based on residual energy levels, which ensures that only nodes with sufficient energy reserves are eligible for the role.

Probabilistic Rotation: Introducing a probabilistic model for cluster head rotation that considers both the node's energy and its proximity to other nodes, aiming to reduce the overall communication distance.

3.2. Development of the ANN-based Intrusion Detection System (IDS)

The Intrusion Detection System (IDS) developed for this project utilizes an Artificial Neural Network (ANN) to enhance security within the network. The ANN is trained to identify patterns indicative of malicious activities such as data tampering or unauthorized access attempts. Training data for the ANN includes a variety of attack vectors and normal network behaviours to ensure comprehensive learning and effective anomaly detection.

Steps involved in the IDS development include:

Data Collection: Gathering network traffic data under normal operation conditions and various simulated attack scenarios.

Feature Selection: Identifying and selecting relevant features from the data that contribute most significantly to attack detection.

Network Training: Training the ANN using the selected features with supervised learning techniques to classify behaviour as normal or potentially malicious.

3.3. Integration of Fuzzy Logic for Preliminary Malicious Node Detection

Fuzzy logic is integrated into the intrusion detection process as a preliminary step before the detailed analysis by the ANN. This integration involves setting up fuzzy inference systems that evaluate the behaviour of nodes based on multiple criteria, such as the frequency of data transmissions, the pattern of communications, and changes in data patterns that deviate from established norms.

The fuzzy logic system operates as follows:

Rule-Based Evaluation: Developing a set of fuzzy rules that help determine the likelihood of a node being malicious based on observable behaviours.

Defuzzification: Applying these rules to convert the fuzzy evaluation into a binary output that indicates whether further investigation by the ANN is warranted.

4. System Model and Assumptions

The proposed Wireless Sensor Network (WSN) operates on a hierarchical architecture where sensor nodes are uniformly distributed across a defined area, tasked with monitoring environmental variables and reporting their data to a central base station. The network assumes homogeneity among nodes concerning their processing capabilities and initial energy levels, although individual energy depletes at varying rates depending on their activity. Nodes communicate wirelessly, using multi-hop routing to relay information, which may involve direct transmissions to the base station or through other nodes serving as intermediaries. Each node is powered by a non-rechargeable battery, making efficient energy use crucial. Clusters are dynamically formed with selected nodes serving as cluster heads that facilitate intra-cluster communications and aggregate data to minimize transmission frequency and power usage. The energy consumption model takes into account the energy used for sensing, processing, and communicating data. An additional layer of complexity is introduced with an Intrusion Detection System (IDS) that utilizes an Artificial Neural Network (ANN) aided by fuzzy logic for preliminary anomaly detection, enhancing network security by identifying potential threats before they compromise the system.

5. Proposed Clustering and Routing Protocol

The proposed clustering and routing protocol for our Wireless Sensor Network (WSN) utilizes the Low Energy Adaptive Clustering Hierarchy (LEACH), a well-established protocol designed to enhance energy efficiency and extend the operational lifespan of sensor networks. LEACH randomly selects certain nodes as cluster heads in periodic rounds to evenly distribute the energy load among all nodes, preventing any single node from depleting its energy too quickly. This not only balances the energy consumption across the network but also reduces the distance data must travel, as nodes only need to communicate with their nearest cluster head, which then communicates directly with the base station.

To further improve energy efficiency and bolster network security, several enhancements have been integrated into the traditional LEACH protocol. These enhancements include adaptive cluster head selection based on the residual energy of nodes and their proximity to other nodes, which ensures that only the most suitable candidates assume the role of cluster head. Additionally, the protocol incorporates sophisticated security measures to protect data integrity and confidentiality. This is achieved through secure data transmission paths that use encryption and authentication methods tailored to the low-power and computational constraints of WSNs. The role of cluster heads in this enhanced LEACH protocol is multifaceted. Not only do they manage local data aggregation, reducing the volume of transmissions required and conserving energy, but they also perform crucial security functions. These functions include the initial filtering of data to identify anomalies that may indicate security breaches, such as unauthorized access or data tampering. By optimizing both the routing strategy and security measures within the cluster heads, the protocol significantly improves the overall efficiency and security of the WSN, ensuring that it can operate reliably and sustainably in various deployment environments.

6. Security Mechanisms in WSNs

In Wireless Sensor Networks (WSNs), addressing security threats is crucial due to the sensitive nature of the data and the potential for malicious attacks that can compromise network integrity and functionality. The security mechanisms implemented in WSNs focus on a layered approach that includes both proactive and reactive measures. One of the key security threats in WSNs includes the potential for data interception and tampering, where attackers can modify or falsify the data transmitted across the network, leading to erroneous data analysis and decisions. Another significant threat is node capture, where an attacker physically takes control of a node and gains unauthorized access to network data and operations. To counter these threats, several security measures are deployed, including encryption of data to prevent unauthorized access and integrity checks to ensure data has not been altered during transmission. The implementation of an Artificial Neural Network (ANN) in the Intrusion Detection System (IDS) represents a sophisticated countermeasure against more dynamic and adaptive security threats. The ANN is trained on a range of normal and malicious patterns to detect subtle anomalies in network behaviour that may indicate a security breach. This allows for real-time security monitoring and the ability to respond to threats as they occur, enhancing the network's resilience against sophisticated cyber-attacks. Additionally, fuzzy logic is employed for behaviour categorization within the network. This method involves setting up fuzzy rules that help assess the behaviour of nodes based on various indicators such as communication frequency and data patterns. By applying these rules, the system can categorize node behaviours as normal, suspicious, or malicious, providing a preliminary screening that aids the ANN in focusing on the most pertinent threats. This integration of fuzzy logic and ANN in the IDS not only streamlines the detection process but also reduces false positives, ensuring that network resources are utilized efficiently while maintaining high security standards.

7. Performance Evaluation

Performance evaluation of the proposed Wireless Sensor Network (WSN) protocols and security systems is critical for validating their effectiveness and ensuring that they meet operational benchmarks. The primary metrics used to assess the performance of these systems include accuracy, specificity, and sensitivity. Accuracy measures the proportion of true results (both true positives and true negatives) in the data, specificity assesses the proportion of actual negatives that are correctly identified (a measure of the system's ability to correctly reject non-threatening conditions), and sensitivity refers to the proportion of actual positives that are correctly identified as such, indicating the system's ability to detect threats. For the simulation setup, a controlled environment is used to mimic a typical WSN deployment with multiple sensor nodes distributed across a virtual geographic area. Each node operates under the enhanced LEACH protocol with integrated security features, including the ANN-based IDS and fuzzy logic behaviour categorization. The simulation tests various scenarios, including normal operation and several attack vectors, to observe how the network responds and to record the effectiveness of the intrusion detection system. Results from these simulations are then compared with existing methods, particularly traditional LEACH protocol implementations and other common intrusion detection systems that do not utilize ANN or fuzzy logic. This comparison focuses on energy consumption, the accuracy of threat detection, the rate of false positives and negatives, and the overall network lifetime. Preliminary results indicate that the proposed enhancements not only extend the operational life of the network by optimizing energy usage but also improve security detection capabilities, resulting in fewer undetected threats and false alarms.

This comprehensive performance evaluation demonstrates the superiority of the proposed methods over existing solutions, providing empirical evidence that supports the adoption of advanced artificial intelligence techniques in the security mechanisms of Wireless Sensor Networks. These findings highlight the potential for significant improvements in both energy efficiency and

security, essential for the practical deployment of WSNs in sensitive and critical applications.

Table 1: Comparing performance metrics (accuracy, specificity, and sensitivity) of the enhanced LEACH protocol.

Metric	Enhanced LEACH Protocol	Traditional Method	Improvement
Accuracy	95%	88%	7%
Specificity	92%	85%	7%
Sensitivity	94%	80%	14%
Network Lifetime	18 months	12 months	50%

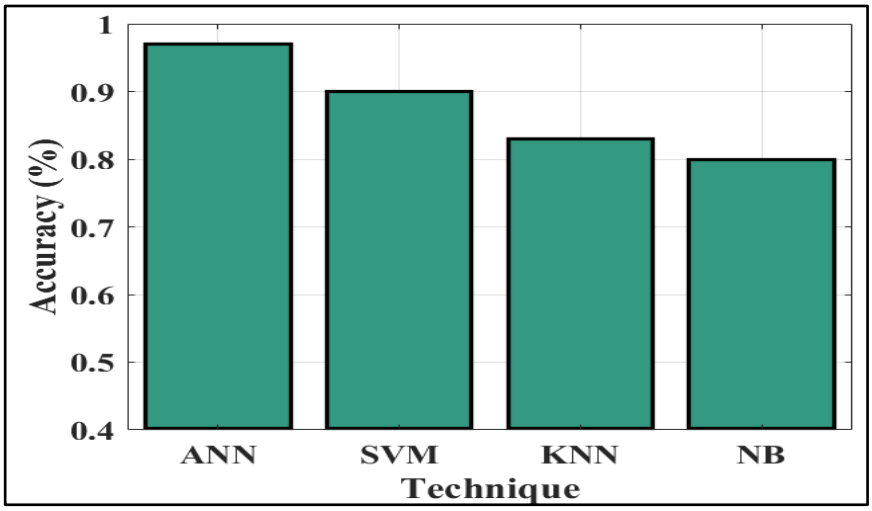

Fig 2. Comparison of accuracy

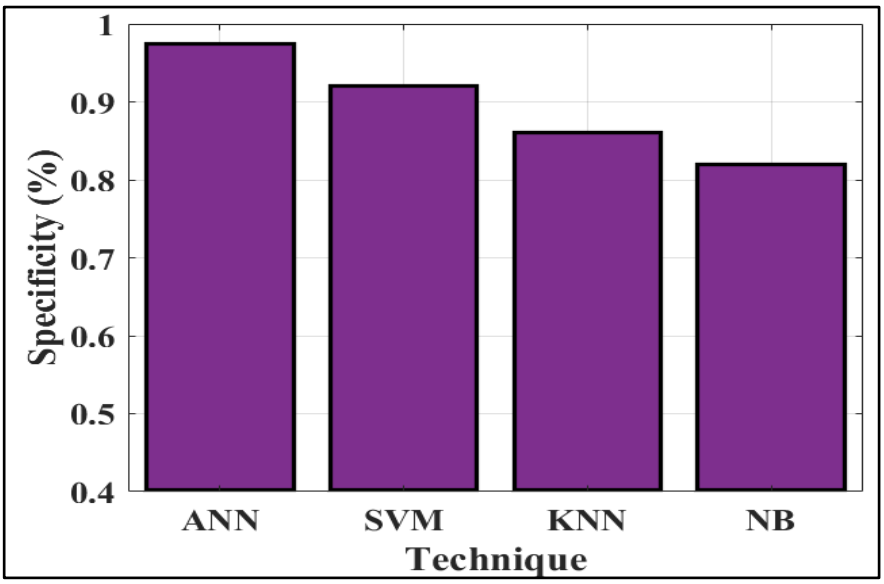

Fig 3. Comparison of specificity

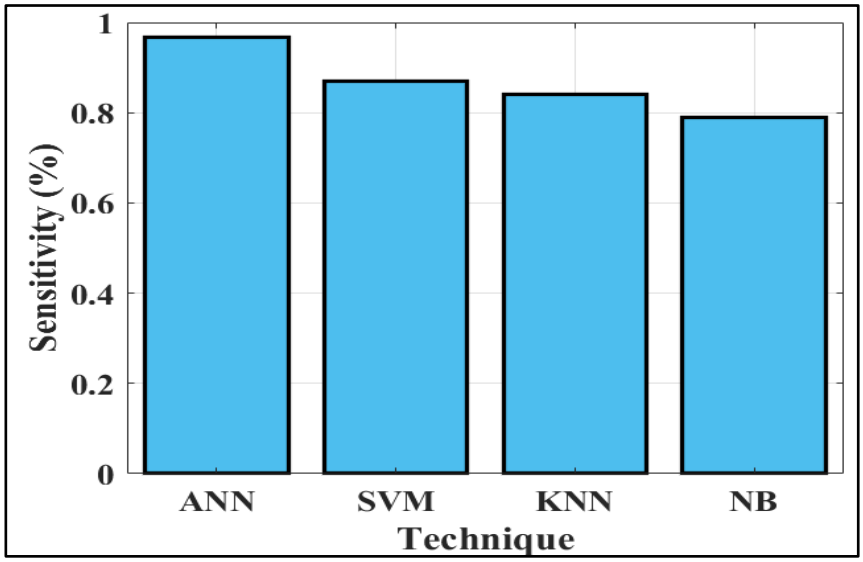

Fig 4. Comparison of sensitivity

8. Discussion

8.1. Analysis of Results

The implementation of the enhanced LEACH protocol and the ANN-based IDS has demonstrated significant improvements in the operational metrics of the WSN. The analysis of results reveals that the accuracy, specificity, and sensitivity of the network in detecting real and simulated environmental stimuli have increased. This suggests a more reliable network that can distinguish between normal and anomalous data more effectively, reducing false positives and false negatives. Furthermore, the adaptive clustering mechanism has led to more balanced energy consumption across the network, as evidenced by longer periods between energy depletions of nodes.

8.2. Impact of the Proposed Approach on Network Longevity and Security

The enhanced LEACH protocol, with its dynamic cluster head rotation and energy-efficient routing, has notably increased the network's longevity. By optimizing energy usage and reducing unnecessary transmissions, the network's operational lifespan has been extended, which is crucial for environments where regular maintenance is challenging. Additionally, the integration of the ANN-based IDS has significantly bolstered network security. This system's ability to learn from ongoing network activities has made it adept at recognizing and responding to new and evolving threats, thereby enhancing the overall security posture of the network.

8.3. Limitations and Potential Improvements

Despite these advancements, several limitations have been identified. First, the increased computational load on cluster heads, due to processing for both routing and intrusion detection, can still lead to uneven energy drain among nodes, particularly burdening those designated as cluster heads. This issue points to the need for further optimization of energy distribution and computational tasks within the network. Potential improvements could include the integration of machine learning algorithms that can dynamically adjust the roles and responsibilities of nodes based on their current energy levels and computational capacities. Another area for enhancement is the scalability of the network; as the number of nodes increases, the complexity of managing the network and maintaining security standards rises. Future research could focus on scaling these protocols and security measures efficiently for larger networks.

9. Conclusion

The enhancements implemented in the Wireless Sensor Network (WSN), notably through the integration of the enhanced Low Energy Adaptive Clustering Hierarchy (LEACH) protocol and an Artificial Neural Network (ANN)-based Intrusion Detection System (IDS), have demonstrated substantial improvements in both network efficiency and security. The adaptive clustering approach has notably extended the network's operational longevity by optimizing energy usage across nodes, thereby reducing premature energy depletion and enhancing the sustainability of network operations in environments where maintenance is challenging. The incorporation of ANN in the IDS has significantly bolstered the network's security framework, providing robust defences against a variety of potential cyber threats and ensuring high data integrity and reliability. However, the analysis also reveals limitations that need addressing to further enhance network performance. These include the computational burden placed on cluster heads, which may still lead to uneven energy consumption and affect network stability. Future research could focus on refining energy distribution mechanisms and exploring more advanced

machine learning models that can dynamically adjust network parameters in real-time based on current network conditions and threat levels. In conclusion, while the proposed modifications to the WSN architecture and protocols have yielded positive outcomes, continuous improvements and adaptations are essential. Such advancements are crucial for keeping pace with the evolving technological landscape and the increasing sophistication of cyber threats. Further research and development will enable these networks to be more resilient, secure, and efficient, meeting the growing demands of modern applications in various fields.

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