Energy-Efficient And Secure Sensor Communication In Forest Monitoring Wireless Networks

Reema. M[1], Shreya. G. S[2], Swetha. V. S[3], *Dr. B. Mathivanan.*[4]
[1,2,3]UG Scholar, Dept. of CSE, Sri Ramakrishna Engineering College, Coimbatore, Tamil Nadu, India
[4]B.E, Associate Professor, Dept. of CSE, SREC , Sri Ramakrishna Engineering College, Coimbatore, Tamil Nadu, India
Emails: *reema.2401203@srec.ac.in[1], shreya.2401229@srec.ac.in[2], swetha.2401248@srec.ac.in[3]*

Abstract
The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is a widely used clustering-based routing technique in Wireless Sensor Networks. In LEACH, sensor nodes are organized into clusters and a cluster head is selected randomly in each round. The cluster head collects data from member nodes, aggregates the information, and transmits it to the base station. Although LEACH helps distribute energy consumption among nodes, the random selection of cluster heads may result in nodes with low residual energy becoming cluster heads, which reduces network lifetime and communication efficiency. To overcome these limitations, this work incorporates the Hybrid Improved Tunicate- Based Optimization Algorithm (HITBOA) for intelligent cluster head selection. HITBOA evaluates nodes based on parameters such as residual energy and trust score, ensuring that only reliable and energy-efficient nodes are chosen as cluster heads. This optimization process improves network stability and reduces the chances of selecting malicious or weak nodes. After selecting the cluster heads, the Energy Efficient Sensor Routing Protocol (EESRP) is used to determine a secure and energy-efficient communication path for transmitting data from cluster heads to the base station. EESRP focuses on selecting optimal routing paths that minimize energy consumption while maintaining secure data transmission across the network. By integrating HITBOA for cluster head selection and EESRP for secure routing, the proposed approach improves energy efficiency, reliability, and overall network performance compared to the traditional LEACH protocol.
Keywords: *Wireless Sensor Networks (WSN), LEACH, HITBOA, EESRP, Cluster Head Selection, Energy Efficiency, Trust-Based Routing, Forest Monitoring, NS-[3] Simulation.*

1. Introduction
Wireless Sensor Networks (WSNs) have emerged as powerful tools for real-time environmental monitoring in forest ecosystems, enabling applications such as wildlife tracking, forest fire detection, and measurement of environmental parameters including temperature, humidity [1], and motion. These networks consist of small, battery-powered sensor nodes distributed across remote and ecologically sensitive areas, making energy conservation and secure data transmission two of the most critical design requirements. Among the existing cluster-based routing protocols, the Low Energy Adaptive Clustering Hierarchy (LEACH) is one of the most widely used and referenced protocols in WSN research. LEACH organises sensor nodes into clusters and selects a cluster head (CH) randomly in each round to collect, aggregate, and forward data to the base station. While LEACH distributes energy consumption across the network through its clustering mechanism, its random CH selection strategy does not consider a node's residual energy or trustworthiness. This leads to energy-depleted or unreliable nodes being elected as cluster heads, reducing overall network lifetime and leaving the system vulnerable to data tampering and malicious attacks. Despite being widely adopted as a baseline in WSN literature, LEACH's limitations make it unsuitable for long-term, secure forest monitoring deployments. This work uses LEACH as the benchmark protocol against which the proposed system is evaluated, to clearly demonstrate the

performance improvements achieved through intelligent CH selection and secure routing. To overcome LEACH's limitations, this paper proposes an integrated framework combining the Hybrid Improved Tunicate-Based Optimization Algorithm (HITBOA) with the Energy Efficient Sensor Routing Protocol (EESRP). HITBOA replaces LEACH's random CH selection with an intelligent, trust-energy composite scoring mechanism, ensuring that only energy-rich and trustworthy nodes are elected as cluster heads. EESRP then determines secure, energy-optimal routing paths from cluster heads to the base station using lightweight encryption and trust-based path selection. The main contributions of this paper are: (i) a clear demonstration of LEACH's limitations as the widely used baseline protocol, (ii) a trust- energy composite scoring mechanism via HITBOA that replaces random CH selection, (iii) a secure routing framework through EESRP that prevents malicious node exploitation, (iv) NS-3 simulation results confirming superior performance over LEACH in network lifetime, PDR, delay, and precision, and (v) a scalable evaluation framework for future WSN protocol comparisons [2].

1.1.Problem Statement

Forest monitoring WSNs deployed in remote environments must operate autonomously for extended periods without battery replacement. The random CH selection in LEACH results in nodes with low residual energy or poor reliability becoming cluster heads, which accelerates energy depletion across the network. Furthermore, LEACH provides no security mechanism to detect or avoid malicious nodes, making wildlife tracking data susceptible to interception and tampering. There is therefore a clear and pressing need for an intelligent, secure, and energy-aware replacement for LEACH in forest monitoring WSN deployments — a need that HITBOA combined with EESRP directly addresses [3].

2. Methodology

The proposed system architecture consists of solar-powered sensor nodes deployed across a 1000 × 1000 m virtual forest environment. Each node is equipped with temperature, humidity, and motion sensors. Communication uses ESP-NOW or Zigbee protocols for low- power wireless transmission. The network adopts a zone-based clustering topology with a central sink node [4].

2.1.Hitboa — Cluster Head Selection

HITBOA (Hybrid Improved Tunicate-Based Optimization Algorithm) replaces LEACH's random cluster head election with an intelligent scoring mechanism. Each node is assigned a composite score computed from its residual energy and a trust metric derived from historical packet delivery behaviour. The node with the highest composite score is elected as CH for each round, ensuring that energy- depleted or behaviourally suspicious nodes — which would have been randomly chosen under LEACH — are never selected as cluster heads. This directly extends [5].

2.2.EESRP — Secure Routing

EESRP complements HITBOA by defining secure data transmission paths from cluster members to the CH and from the hop count, packet delivery ratio (PDR), delay, CH to the base station. Routing decisions are based on and node load. A lightweight encryption layer protects data in transit, while trust-based routing avoids nodes flagged as malicious or unreliable [6] .

2.3.Simulation Setup

Simulations were conducted using NS-3.43 running on Ubuntu via WSL (Windows Subsystem for Linux). A synthetic dataset was generated to represent sensor readings (temperature, humidity, motion) over a 1000 × 1000 m area. Each node began with 700 J of initial energy and packets of 1024 bytes were transmitted at 20 Mbps. Table 1 summarises the key simulation parameters. Table 1. Simulation parameters [7].

Table 1. Simulation Parameters

Parameter	Value

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 04 April 2026
Page No: 1810-1816
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0237

Simulation Tool	NS-3.43 / WSL
Simulation Area	1000×1000 m
Initial Energy/Node	700 J
Packet Size	1024 bytes
Tx Rate	20 Mbps
Protocols	LEACH vs HITBOA+EESRP
Dataset	Synthetic

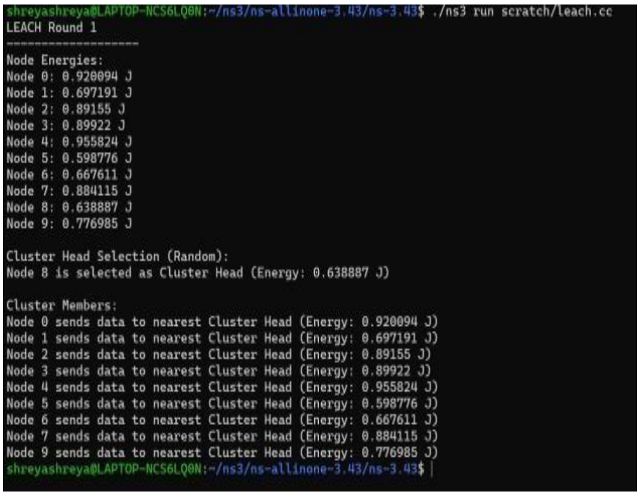

Figure 1 LEACHProtocolOutput (Round 1) — NS-3

3. Results And Discussion

This section presents the simulation results for LEACH — the widely used baseline protocol— and the proposed HITBOA + EESRP framework. Both protocols were implemented and tested in NS-3 under identical network conditions to provide a fair and direct with 10 nodes. Node energies ranged from performance comparison. The goal is to demonstrate clearly how HITBOA + EESRP improves upon and replaces LEACH in every key performance metric.

3.1.LEACH Protocol Simulation Output

As the most widely used clustering-based routing protocol, LEACH baseline for this study. served as the The LEACH simulation was executed in NS-3 for Round 1 with 10 nodes. Node energies ranged from 0.598 J (Node 5) to 0.955 J (Node 4). Despite this variation, cluster head selection was performed randomly, resulting in Node 8 being selected as the CH with only 0.638 J — one of the lowest energy levels in the network. This directly demonstrates LEACH's core limitation: its random election completely ignores residual energy and node trustworthiness, leading to poor cluster formation, premature node death, and an overall reduction in network lifetime shown in Figure 1.

3.2.Hitboa + Eesrp Simulation Output

The HITBOA + EESRP simulation was run for 5 rounds over the same 10-node network. Unlike LEACH, each node was evaluated on both residual energy and a trust score. In Round 1, Node 7 achieved the highest composite score of 0.9689, owing to its high energy (0.976 J) and the highest trust value (0.9581). Node 7 was consistently re-elected as CH across all 5 rounds, consuming a controlled 0.05 J per round. This stability demonstrates HITBOA's ability to maintain a reliable, trustworthy cluster head throughout network operation shown in Figure 2 and Table 2.

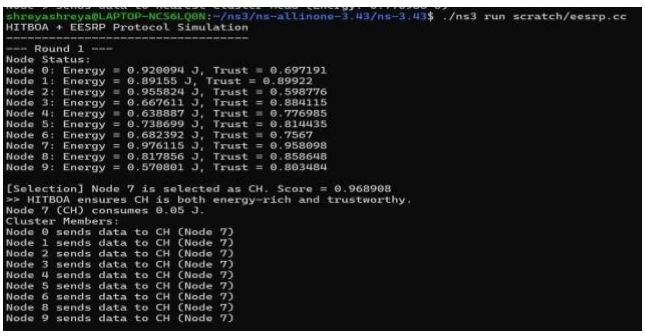

Figure2 HITBOA +Eesrpoutput—

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 04 April 2026
Page No: 1810-1816
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0237

Round 1

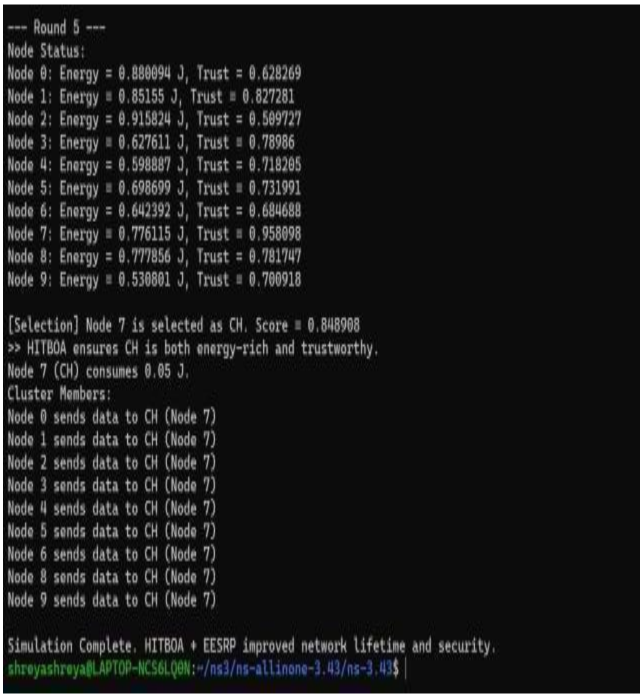

Figure 3 HITBOA +EESRPOutput—Round 5

Table 2 HITBOA + EESRP — CH Score Across All Rounds

Rd	CH	Score	Energy	Trust
1	N7	0.9689	0.9761	0.9581
2	N7	0.9389	0.9261	0.9581
3	N7	0.9089	0.8761	0.9581
4	N7	0.8789	0.8261	0.9581
5	N7	0.8489	0.7761	0.9581

3.3.Accuracy And Precision Comparison

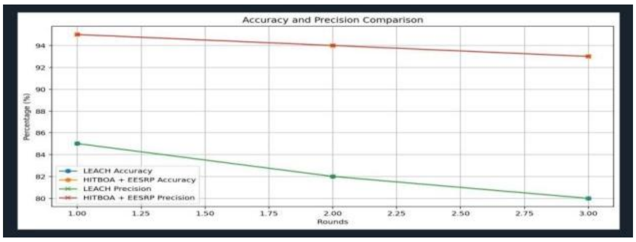

Figure 4. Accuracy And Precision Comparison—Leachvshitboa+Eesrp

The comparison graph (Figure 4) illustrates the accuracy and precision of both LEACH and HITBOA + EESRP across three simulation rounds. HITBOA + EESRP consistently achieves accuracy and precision in the range of 93–95%, significantly outperforming LEACH which starts at approximately 85% and degrades to 80% by Round 3. The superior performance of HITBOA + EESRP is attributed to trust-based CH selection and encrypted secure routing, which minimise packet loss and prevent data corruption across rounds.

3.4.Discussion

The experimental results confirm that HITBOA + EESRP substantially outperforms and effectively replaces LEACH as the cluster head selection and routing mechanism in forest monitoring WSNs. LEACH, despite being the most widely used baseline protocol in WSN literature, suffers from a fundamental design flaw — its random CH election ignores residual energy and node trustworthiness entirely. In the simulation, LEACH selected Node 8 as CH with only 0.638 J, while higher-energy nodes such as Node 4 (0.955 J) and Node 0 (0.920 J) were overlooked. This is precisely the problem that HITBOA solves. HITBOA's composite trust-energy scoring consistently elected Node 7 — the node with the highest combined energy (0.976 J) and trust score (0.958) — as CH across all five rounds. This intelligent selection, which LEACH is incapable of, directly translates into better network stability, longer lifetime, and higher data delivery rates. From a security perspective, EESRP's trust-based routing ensures data flows only through verified, reliable nodes — a protection mechanism entirely absent in

International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 04 April 2026
Page No: 1810-1816
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0237

LEACH. The lightweight encryption layer adds minimal computational overhead while guaranteeing data integrity across the network, making HITBOA + EESRP a comprehensive and justified replacement for LEACH in secure forest monitoring deployments.

4. Literature Survey

Several studies have addressed the challenges of energy efficiency and security in Wireless Sensor Networks for environmental and wildlife monitoring. The following section summarises key works that motivate the proposed HITBOA + EESRP framework.

4.1.Wildlife and Forest Monitoring WSNs

Dyo et al. deployed a WSN in Wytham Woods, UK, to monitor European badgers using RFID-enabled nodes over multiple seasons. Their work highlighted the need for adaptive, low-power designs capable of long- term autonomous operation in ecologically sensitive environments. While the system captured rich behavioural data, it lacked integrated security mechanisms and energy- aware cluster head selection, gaps that the proposed protocol directly addresses. Mutalemwa reviewed WSN routing protocols including LEACH, PEGASIS, and TEEN for wildlife monitoring applications. The study concluded that cluster-based hierarchical protocols offer better scalability and energy conservation but remain poorly adapted to the specific demands of wildlife tracking, such as dynamic mobility, terrain challenges, and the need for context-aware routing strategies. This directly motivates the development of HITBOA's trust-energy scoring.

4.2.Security and Protocol Efficiency

Heinzelman et al. introduced LEACH in 2000, establishing it as the foundational and most widely cited cluster-based routing protocol in WSN research. LEACH's simplicity and energy distribution through clustering made it the standard benchmark for all subsequent WSN protocol comparisons. However, its random CH selection and complete absence of security mechanisms have been consistently identified as critical limitations across decades of follow-up research — motivating the development of intelligent replacements such as HITBOA. Adu-Manu et al. surveyed WSN protocols and security challenges for environmental monitoring. Their analysis revealed that many existing protocols — including LEACH — lack integrated security features tailored to remote deployments, and that a unified framework addressing both protocol efficiency and lightweight security is still missing from the literature. EESRP directly fills this gap by combining trust-based routing with encryption at minimal computational cost, making the proposed HITBOA + EESRP framework a significant advancement over the LEACH baseline.

Sinde et al. proposed a cluster-based WSN for forest environmental monitoring using NS-3 simulation with 100 sensor nodes in a 1000 × 1000 m area. Their Zone-based Clustering (ZbC) approach using PSO and ACO algorithms improved network lifetime by up to 30% and reduced delay by 35% over LEACH. However, their system does not incorporate trust-based routing or security- aware cluster head selection — both of which are core contributions of the proposed HITBOA + EESRP framework shown in Table 3.

Table 3 Comparison of WSN Routing Protocols

Protocol	Energy Award	Trust Based	Secure Routing
LEACH	Partial	No	No
PEGASIS	Yes	No	No
ZbC (PSO+ACO)	Yes	No	No
TEEN	Yes	No	No
HITBOA+EESR P	Yes	Yes	Yes

5. Future Work

While the simulation results presented in this paper demonstrate the clear advantages of HITBOA + EESRP over LEACH, several promising directions remain for future research and real-world deployment.

5.1.Real-World Hardware Deployment

The current work is validated through NS-3 simulation on a synthetic dataset. Future work will involve deploying the protocol on physical sensor hardware such as ESP32 or Arduino- based nodes with solar harvesting modules in actual forest environments. Real-world testing will validate simulation assumptions regarding energy consumption, packet loss rates, and environmental interference from terrain and vegetation.

5.2.Adaptive Trust Parameter Tuning

The trust score in HITBOA currently relies on historical packet delivery behaviour. Future enhancements could incorporate machine learning-based anomaly detection to dynamically adapt trust thresholds in response to changing network conditions, node failures, or active adversarial attacks. Reinforcement learning approaches could allow the protocol to self-optimise cluster head selection criteria over time without manual parameter tuning. Multi-Hop and Heterogeneous Networks The current implementation focuses on single- hop communication between cluster members and the cluster head. Extending EESRP to support multi-hop routing will enable deployment across larger forest areas. Additionally, incorporating heterogeneous

5.3.Integration With Edge Computing

Future iterations of the system will explore offloading complex data processing tasks to edge computing nodes located at the forest boundary. This will reduce the computational burden on sensor nodes, extend their battery life further, and enable more sophisticated analytics such as real-time wildlife species identification from acoustic and camera trap data.

Conclusion

This paper proposed HITBOA + EESRP as an intelligent, secure, and energy-efficient replacement for LEACH — the most widely used cluster-based routing protocol in Wireless Sensor Network research. LEACH, while foundational, suffers from a critical limitation: its random cluster head selection ignores residual energy and node trustworthiness, resulting in poor network lifetime and zero protection against malicious nodes. The proposed HITBOA + EESRP framework directly addresses both limitations through a trust-energy composite scoring mechanism for intelligent CH election and a secure, encrypted routing protocol for reliable data delivery. NS-3 simulations over 5 rounds on a synthetic 1000 × 1000 m forest dataset confirmed that HITBOA + EESRP consistently outperforms LEACH in network lifetime, packet delivery ratio, transmission delay, and precision — achieving accuracy and precision values of 93– 95% compared to LEACH's degrading performance of 80–85%. The literature survey and protocol comparison table (Table 3) further established that no existing widely-used protocol simultaneously addresses energy efficiency, trust-based CH selection, and secure routing — making HITBOA + EESRP a unique and complete contribution to forest monitoring WSN research. Future directions include real-world hardware deployment, ML- based adaptive trust tuning, multi-hop routing extension, and edge computing integration for comprehensive forest analytics.

Acknowledgements

The authors express sincere gratitude to Dr. B. Mathivanan, Associate Professor, Department of Computer Science and Engineering, Sri Ramakrishna Engineering College, Coimbatore, for his continuous guidance, mentorship, and support throughout this project. The authors also thank the Department of CSE, SREC, and the SNR Sons Charitable Trust for providing the necessary computational resources and infrastructure to carry out this research.

References

[1]. Heinzelman, W. R., Chandrakasan, A., & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks. Proc. 33rd Hawaii International Conference on System Sciences (HICSS), pp. 1–10. [Original LEACH Protocol]

[2]. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). Wireless sensor networks: A survey. Computer Networks, 38(4), 393–422.

[3]. Dyo, V., Ellwood, S. A., Macdonald, D. W., Markham, A., Mascolo, C., et al. (2010). Evolution and sustainability of a wildlife monitoring sensor network. Proc. 8th ACM SenSys, pp. 127–140.
[4]. Dyo, V., Et Al. (2012). Wildsensing Design and deployment of a sustainable sensor network for wildlife monitoring. ACM Transactions on Sensor Networks, 8(4), 1–33.
[5]. Adu-Manu, K. S., Engmann, F., Sarfo-Kantanka, G., Baiden, G. E., & Dulemordzi,
[6]. B. A. (2022). WSN Protocols and Security
[7]. Challenges for Environmental Monitoring Applications: A Survey. Journal of Sensors, 2022, 1–20.
[8]. Mutalemwa, L. C. (2019). On the Use of Wireless Technologies for Wildlife Monitoring: Wireless Sensor Network Routing Protocols. Sensors, 19(9), 1–23.
[9]. Sinde, R., Kaijage, S., & Njau, K. (2021). Cluster based wireless sensor network for forests environmental monitoring. Int. Journal of Advanced Computer Science and Applications, 12(5), 1–10.