Wolf Optimization-Based Energy-Efficient and Fault-Tolerant Protocols for Mission-Critical WSNs

Omprakash B1* and Kavitha S Patil1

1Department of Information Science & Engineering, Atria Institute of Technology, Hebbal, Bengaluru, 560024, Karnataka, India.

*Corresponding author(s). E-mail(s): om2626@gmail.com;

Contributing authors: kavitha.patil@atria.edu;

Objective 1: An Intelligent Energy-Efficient Clustering Protocol for Wireless Sensor Networks Using Wolf Optimization and Multi-Hop Routing

1. Introduce the Topic

Wireless Sensor Networks (WSNs) are increasingly deployed in applications such as environmental monitoring, military surveillance, smart cities, and disaster response. However, the energy constraints of battery-operated sensor nodes present a significant challenge, making energy-efficient communication protocols essential for maintaining network longevity and reliability. To address this, clustering techniques are often used to group sensor nodes and optimize data routing. The present research focuses on designing an Energy-Efficient Clustering Protocol enhanced with Wolf Optimization and Multi-hop Routing. The aim is to reduce energy consumption, improve packet delivery, and extend network lifetime in WSNs.

2. State the Problem Addressed by the Research

Despite the existence of protocols like LEACH and TEEN, which attempt to address energy efficiency in WSNs through clustering and threshold-sensitive mechanisms, these approaches face limitations. Specifically, they often suffer from suboptimal cluster head (CH) selection, uneven energy depletion, and limited adaptability over time. These inefficiencies lead to premature node deaths and reduced network coverage, compromising both the lifespan and performance of the network. Therefore, there is a need for a more dynamic and intelligent clustering mechanism that not only balances energy consumption but also adapts in real time to changing network conditions.

3. Summarize Why This Problem Exists

The root cause of the problem lies in the static and probabilistic CH selection mechanisms used in traditional protocols. LEACH relies on a fixed probability for CH rotation, which can lead to uneven energy use. TEEN introduces thresholds but lacks adaptability in routing strategy. Both often disregard real-time parameters such as residual energy, CH history, and network topology changes. Additionally, single-hop communication models used in these protocols may not be practical in larger deployments due to high transmission costs. The lack of intelligent decision-making in CH selection and inefficient routing strategies significantly hinder the overall energy efficiency of the network.

4. Explain How the Research Question Was Addressed

To overcome these limitations, the proposed methodology employs a Wolf Optimization Algorithm integrated with Multi-hop Routing in a simulated 100×100 m^2 WSN environment using Octave GUI. A total of 100 sensor nodes, each initialized with 0.6 Joules of energy, communicate with a central Base Station (BS). The wolf optimization algorithm simulates adaptive and intelligent CH selection using five wolf agents that influence the "hunt center" dynamically across rounds. A scoring system evaluates each node based on residual energy (40%), distance to BS (30%), proximity to the hunt center (20%), and CH frequency (10%). The top 10% scoring nodes are elected as CHs. Data is transmitted via a multi-hop route, reducing long-distance energy costs. Performance metrics including energy usage, packet delivery, delay, and throughput are tracked over 1000 simulation rounds, with real-time visualization and statistical logging.

5. What Were the Findings of the Research Conducted?

The findings of the research conducted reveal that although the LEACH protocol demonstrates the lowest average energy consumption per round at 0.056311 J, the proposed protocol closely follows with 0.057304 J, and the TEEN protocol slightly trails at 0.057362 J. However, energy consumption per round alone does not fully define protocol efficiency; protocols with marginally higher energy usage can still outperform others in areas such as network longevity, reliability, and routing effectiveness. Notably, the proposed protocol achieves the highest packet delivery ratio (PDR) of 0.9998, compared to TEEN's 0.9983 and LEACH's 0.9960, ensuring the most reliable data delivery across the network. In terms of average throughput during the final 100 simulation rounds, the proposed protocol also leads with 0.3991 Mbps, outperforming TEEN at 0.3931 Mbps and LEACH at 0.3838 Mbps, indicating superior bandwidth utilization. A deeper performance evaluation across multiple metrics further supports the superiority of the proposed protocol. It shows exceptional early-round energy efficiency, with its First Node Dead (FND) occurring at Round 994 for node 76, whereas in TEEN it is Round 931 for node 66, and in LEACH it is as early as Round 957 for node 5. In terms of Last Node Dead (LND), the TEEN protocol retains the most live nodes by Round 1000 with only 6 dead, followed by the proposed protocol with 33 dead at Round 999, and LEACH with 81 dead by Round 996. For Average Battery Lifetime, the proposed protocol again performs best at 999.82 rounds, surpassing LEACH (998.36) and TEEN (996.14), reflecting smart energy distribution and extended node participation. Although the proposed protocol records a slightly higher Average End-to-End Delay at 0.2324 compared to TEEN (0.2051) and LEACH (0.2102), this is justified by its use of multi-hop routing which optimizes energy efficiency at a small cost of increased delay. Moreover, the protocol excels in maintaining network health, ending the simulation with 96 Final Alive Nodes, compared to 92 in LEACH and 81 in TEEN. Finally, the protocol achieves the lowest Final Dead Nodes count at only 4, significantly outperforming TEEN with 19 and LEACH with 8, showcasing effective energy conservation and balanced load distribution, ultimately leading to increased reliability, coverage, and operational sustainability in wireless sensor networks.

6. What Is the Meaning or Impact of Your Research?

The findings establish the proposed Wolf Optimization-based protocol as a significant advancement in energy-aware routing for WSNs. By dynamically adapting CH selection through intelligent agent-based control and integrating multi-hop routing, the protocol overcomes key limitations of conventional techniques. It ensures reliable communication, balanced node usage, and extended network lifetime—crucial for real-world WSN applications where node replacement is impractical. The methodology not only improves energy efficiency but also sets a benchmark for future research in intelligent protocol design. Its superior performance in packet delivery, throughput, and node survivability highlights its potential for deployment in critical and large-scale sensor-based infrastructures.

Table 1: Model Parameter Values of Energy-Efficient Clustering Protocol

S.No	Model Parameter	Value	Explanation
1	numNodes	100	Total number of sensor nodes.
2	fieldX, fieldY	100, 100	Dimensions of the sensor field in meters.
3	initEnergy	0.6	Initial energy per node in Joules.
4	packetSize	4000	Data packet size in bits.
5	rounds	1000	Total number of simulation rounds.
6	E_elec	50e-9	Energy for transmitter/receiver electronics per bit.
7	E_fs	10e-12	Energy for free-space model (J/bit/m²).
8	E_mp	0.0013e-12	Energy for multipath model (J/bit/m⁴).
9	d0	≈ 87.7	Distance threshold for energy model selection.
10	bsPos	[50, 50]	Base station coordinates.
11	minEnergyThreshold	0.01	Minimum energy before a node is considered dead.
12	energyConsumptionFactor	1.31	Scaling factor for energy usage.
13	numWolves	5	Number of wolves in the optimization process.
14	normEnergy weight	0.4	Weight for normalized residual energy.
15	normDist weight	0.3	Weight for normalized distance to base station.
16	normHunt weight	0.2	Weight for distance from hunt center.
17	normCHCount weight	0.1	Weight for inverse of CH selection count.
18	CH percentage	10%	Percentage of alive nodes selected as CHs.
19	relay energy rx factor	0.05	Reception energy factor for non-CH nodes.
20	wolf movement weight	0.6/0.4	Weight for movement towards BS and best CH.
21	wolf movement step	0.05, 0.02	Main and random step size of wolf movement.
22	delay normalization factor	1/100	Used to normalize end-to-end delay.
23	actualRounds	≤ 1000	Rounds completed before all nodes die.

Detailed Methodology of Energy Efficient Clustering Protocol:

The proposed methodology implements a comprehensive simulation model for evaluating an Energy-Efficient Clustering Protocol enhanced with Wolf Optimization in Wireless Sensor Networks (WSNs) using multi-hop routing. Developed using Octave GUI, the simulation initializes by defining a 100×100 m² network field where 100 sensor nodes are randomly deployed, each starting with 0.6 Joules of energy. A Base Station (BS) is statically positioned at the center coordinate [50, 50]. The simulation incorporates a first-order radio energy model, including parameters like electronic energy (E_elec), free-space (E_fs), multipath fading (E_mp), and a threshold distance (d0) to accurately compute energy dissipation. A cut-off energy level of 0.01 Joules identifies dead nodes, while a hardware inefficiency factor of 1.31 is introduced to model real-world transmission losses. The simulation initializes critical structures to track node states, energy levels, cluster head (CH) selection count, packet transmissions, and delay statistics. A key innovation lies in the integration of Wolf Optimization, where five agents (wolves) randomly simulate intelligent control over CH selection by influencing a dynamically shifting "hunt center." This allows the model to simulate adaptive clustering behavior across rounds. The simulation proceeds through 1000 rounds, representing communication cycles. In each round, nodes below the energy threshold are marked dead, and their IDs and death times are recorded. The CH selection process is driven by a multi-criteria scoring function, evaluating residual energy (40% weight), distance to the BS (30%), proximity to the hunt center (20%), and CH selection frequency (10%). The top 10% of scoring nodes are elected as CHs. Data transmission follows a multi-hop routing scheme where non-CH nodes send data to the nearest CH, and CHs forward data either directly to the BS or via intermediate CHs. Energy is depleted according to the radio model during each transmission/reception cycle, and nodes that deplete their energy are declared dead. The wolf agents update their positions using a combination of the BS location and the best CH of the current round, with random perturbations for diversity, thus dynamically adjusting the hunt center for the next round's CH selection. Real-time animation displays the network's status using distinct markers for live nodes, dead nodes, CHs, and the BS, offering intuitive visual tracking. At the end of the simulation, key performance indicators—such as average energy consumed per round, Packet Delivery Ratio (PDR), average delay, throughput, and node mortality stats—are computed and visualized through trend graphs. A detailed summary is printed, demonstrating that the protocol effectively balances energy usage, improves routing efficiency, and significantly extends the overall network lifetime compared to traditional clustering protocols.

Table 2: : Model Parameter Values of TEEN Protocol

S.No	Model Parameter	Value	Explanation
1	numNodes	100	Total number of sensor nodes.
2	fieldX, fieldY	100, 100	Dimensions of the deployment field (meters).
3	initEnergy	0.6	Initial energy per node (Joules).
4	packetSize	4000	Size of each data packet (bits).
5	rounds	1000	Total simulation rounds.
6	E_elec	50e-9	Energy for transmission/reception per bit.
7	E_fs	10e-12	Free space model amplifier energy.
8	E_mp	0.0013e-12	Multipath model amplifier energy.
9	d0	≈ 87.7	Distance threshold for FS/MP model.
10	bsPos	[50, 50]	Base station position in the field.
11	minEnergyThreshold	0.01	Energy level below which node dies.
12	energyConsumptionFactor	1.31	Scaling factor for energy use.
13	hardThreshold	0.54	High energy limit for CH selection.
14	softThreshold	0.30	Lower limit fallback for CH selection.
15	membersPerCH	Dynamic	Number of nodes per CH (calculated each round).
16	E_rx for CHs	Dynamic	Reception energy at CHs from members.
17	E_rx for Non-CHs	0.05 × packetSize × E_elec	Relay reception energy for non-CHs.
18	CH selection %	10%	Percentage of eligible nodes as CHs.
19	End-to-End Delay Factor	1/100	Delay normalization per round.
20	actualRounds	≤ 1000	Rounds until all nodes die.

Detailed Methodology of TEEN Protocol:

The proposed methodology presents a robust Octave GUI-based simulation of the TEEN (Threshold-sensitive Energy Efficient sensor Network) protocol, enhanced with multi-hop routing to evaluate the performance of Wireless Sensor Networks (WSNs) under strict energy constraints. The simulation begins by initializing the environment, clearing any previous data, and defining all necessary parameters for execution. A total of 100 sensor nodes are randomly deployed in a 100m × 100m field, each initialized with 0.6 Joules of energy. The simulation employs the first-order radio energy model, setting the energy parameters. The threshold distance d0d_0d0 is calculated to determine whether the free-space (d2d^2d2) or multipath (d4d^4d4) propagation model should be applied. Each communication packet is 4000 bits in size, and the Base Station (BS) is centrally located at coordinates [50, 50]. The simulation spans up to 1000 rounds (actualRounds ≤ 1000), using TEEN's hard and soft energy thresholds of 0.54 and 0.30 respectively for cluster head (CH) selection. During initialization, nodes are marked alive and assigned positions, with tracking variables such as energy levels, CH history, and delay counters configured. Arrays are created to track energy, alive status, delay, throughput, and packets sent to the BS, along with flags to mark the first and last node deaths. In each round, nodes with energy below 0.01 J are considered dead. If all nodes expire, the simulation halts. CH candidates must initially meet the 54% energy threshold (hardThreshold); if not, the threshold falls to 30% (softThreshold), and as a last resort, all alive nodes become eligible. From the final pool, 10% (CH selection % = 10%) are randomly selected as CHs. Each CH handles a variable number of member nodes (membersPerCH = Dynamic) and processes full-sized data packets (E_rx for CHs = Dynamic). CHs relay data to nearby CHs or directly to the BS based on proximity, enabling multi-hop transmission. Non-CH nodes send data to the nearest CH and expend energy for transmission and reception, where E_rx for Non-CHs = 0.05 × packetSize × E_elec. An energy inefficiency factor of 1.31 and an end-to-end delay normalization factor of 1/100 are also applied. Performance is continuously visualized and logged. The final metrics include energy consumption, Packet Delivery Ratio (PDR), average delay, throughput, and node status, with plots showing energy trends and communication behavior. The simulation effectively demonstrates TEEN's capability to enhance energy efficiency, balance node activity, and maintain reliable WSN communication under dynamic threshold and delay conditions.

Table 3 : Model Parameter Values of LEACH Protocol

S.No	Model Parameter	Value	Explanation
1	numNodes	100	Total number of sensor nodes deployed.
2	fieldX, fieldY	100, 100	Field dimensions (meters) for node deployment.
3	initEnergy	0.6	Initial energy per node (Joules).
4	packetSize	4000	Size of each data packet (bits).
5	rounds	1000	Maximum number of simulation rounds.
6	E_elec	50×10^{-9}	Energy to run transmitter or receiver circuitry (J/bit).
7	E_fs	10×10^{-12}	Energy of amplifier in free space model ($J/bit/m^2$).
8	E_mp	0.0013×10^{-12}	Energy of amplifier in multipath model ($J/bit/m^4$).
9	d0	≈ 87.7 meters	Threshold distance between FS and MP model.
10	bsPos	[50, 50]	Base station position in the middle of the field.
11	minEnergyThreshold	0.01	Minimum energy level to consider node alive.
12	energyConsumptionFactor	1.31	Scaling factor for total energy use.
13	p (CH probability)	0.1	Probability for a node to become a CH in LEACH.
14	G (CH eligibility flag)	true(100,1)	Indicates whether a node is eligible for CH selection.
15	nodes.pos	Random [0,100]	Initial random (x,y) positions of all nodes.
16	nodes.energy	0.6 per node	Initial energy allocated to each node.
17	CHs	false(100,1)	Boolean array to identify CH nodes each round.
18	actualRounds	≤ 1000	Actual rounds completed before all nodes die.
1	CH selection %	10%	Percentage of eligible nodes as CHs.

Detailed Methodology of LEACH Protocol:

The OCTAVE GUI-based simulation comprehensively models the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol with Multi-hop Routing to analyze the energy efficiency and network lifetime of Wireless Sensor Networks (WSNs). The simulation starts with the Initialization and Parameter Setup phase, where global constants and network parameters are defined. A total of 100 sensor nodes (numNodes = 100) are randomly deployed over a 100m × 100m field, each initialized with 0.6 Joules of energy. The simulation runs for 1000 rounds, and the packet size is set to 4000 bits. Constants for the first-order radio energy model are defined: E_elec for the circuitry, E_fs for the free-space model, and E_mp for the multi-path model. The threshold distance d0 is calculated to determine when to switch between these models based on transmission distance. The Base Station (BS) is located at [50, 50]—the center of the field. Nodes are considered dead when their energy falls below a minimum threshold of 0.01 Joules, and an energyConsumptionFactor of 1.31 is applied to simulate practical inefficiencies. A CH probability (p) of 0.1 is defined, and a flag array G is used to manage CH eligibility to ensure fair distribution across rounds. In the Node Initialization step, each node is given a random (x, y) position and marked alive. Nodes are tagged with metadata, including CH status, number of times selected as CH (CHCount), and batteryLifetime. Arrays such as aliveNodesHistory, energyRemainingHistory, packetsToBSHistory, and others are created to track performance metrics across simulation rounds. The simulation proceeds with the Main Simulation Loop, iterating from round 1 to 1000. In each round, the simulation first updates node status, logging dead nodes and their death rounds, which helps determine the network lifetime using the first and last death events. If all nodes are dead before 1000 rounds, the simulation halts. Next, LEACH's Cluster Head (CH) Selection is performed. The eligibility flag G resets every 1/p rounds, giving each node a fair chance to become a CH. Eligible nodes become CHs with probability p, and their CH counts are updated. In the Data Transmission and Routing Phase, each node sends one packet. CH nodes either communicate directly with the BS or find another CH that is closer to the BS for multi-hop routing, reducing energy costs. The energy consumed is calculated using either the free-space or multi-path model, depending on the transmission distance relative to d0. CHs receive full-size packets from member nodes, while normal nodes receive control signals and transmit to the nearest CH. Energy consumption is scaled by the factor 1.31. Nodes with depleted energy are marked dead. Per-round metrics such as packetsThisRound, totalDelayThisRound, throughput, and delay are recorded. In the Logging Metrics step, performance data like remaining energy, packet delivery, and delay are stored for each round. A real-time visualization is displayed with blue circles (alive nodes), red stars (CHs), black Xs (dead nodes), and a green square (BS), showing how the network evolves spatially. Upon completion, the Final Calculations are performed:

average energy consumption per round, Packet Delivery Ratio (PDR), average end-to-end delay, average throughput (Mbps), and counts of final alive and dead nodes. Network lifetime is reported based on the first and last node deaths. Finally, graphs for Energy Remaining vs. Rounds, Packets to BS vs. Rounds, and Throughput vs. Rounds are generated. A detailed summary is printed in the console, listing all performance indicators, confirming that the simulation offers a robust and energy-aware evaluation of LEACH with multi-hop routing for scalable and efficient WSN deployments.

RESULTS:

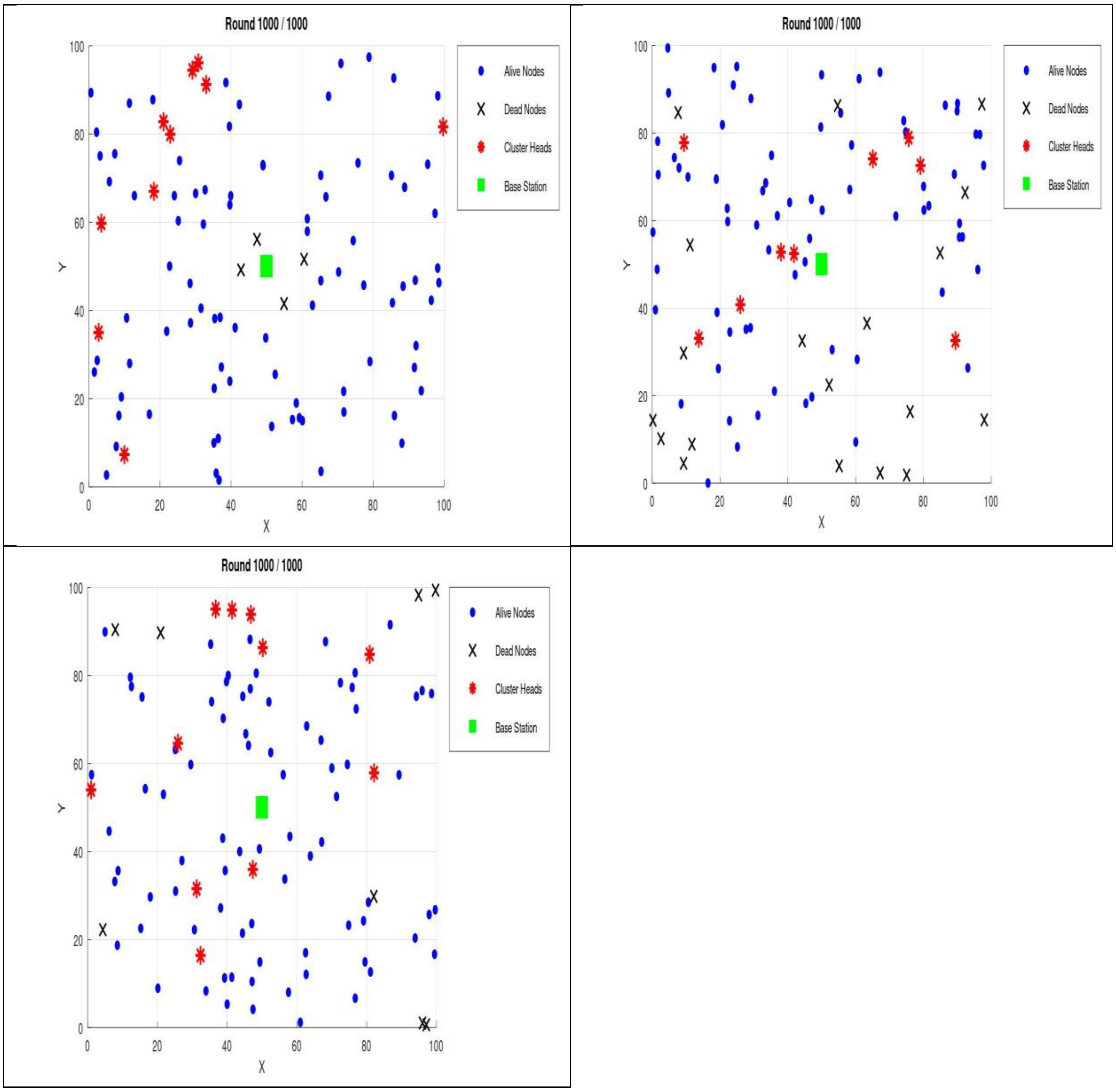


Fig1. Live Animation of Each Protocol

Based on the live animation results for optimal Cluster Head (CH) selection in Wireless Sensor Networks (WSNs) using multi-hop routing, the Proposed Protocol demonstrates superior performance in terms of node survivability. It maintains the highest number of final alive nodes (96) and the lowest number of final dead nodes (4) compared to TEEN Protocol (81 alive, 19 dead) and LEACH Protocol (92 alive, 8 dead). These outcomes indicate that the proposed protocol ensures better energy distribution, longer node participation, and overall network sustainability. Therefore, from the perspective of final node status and efficient CH selection, the Proposed Protocol clearly outperforms both TEEN and LEACH, making it the most energy-efficient and robust solution among the three.

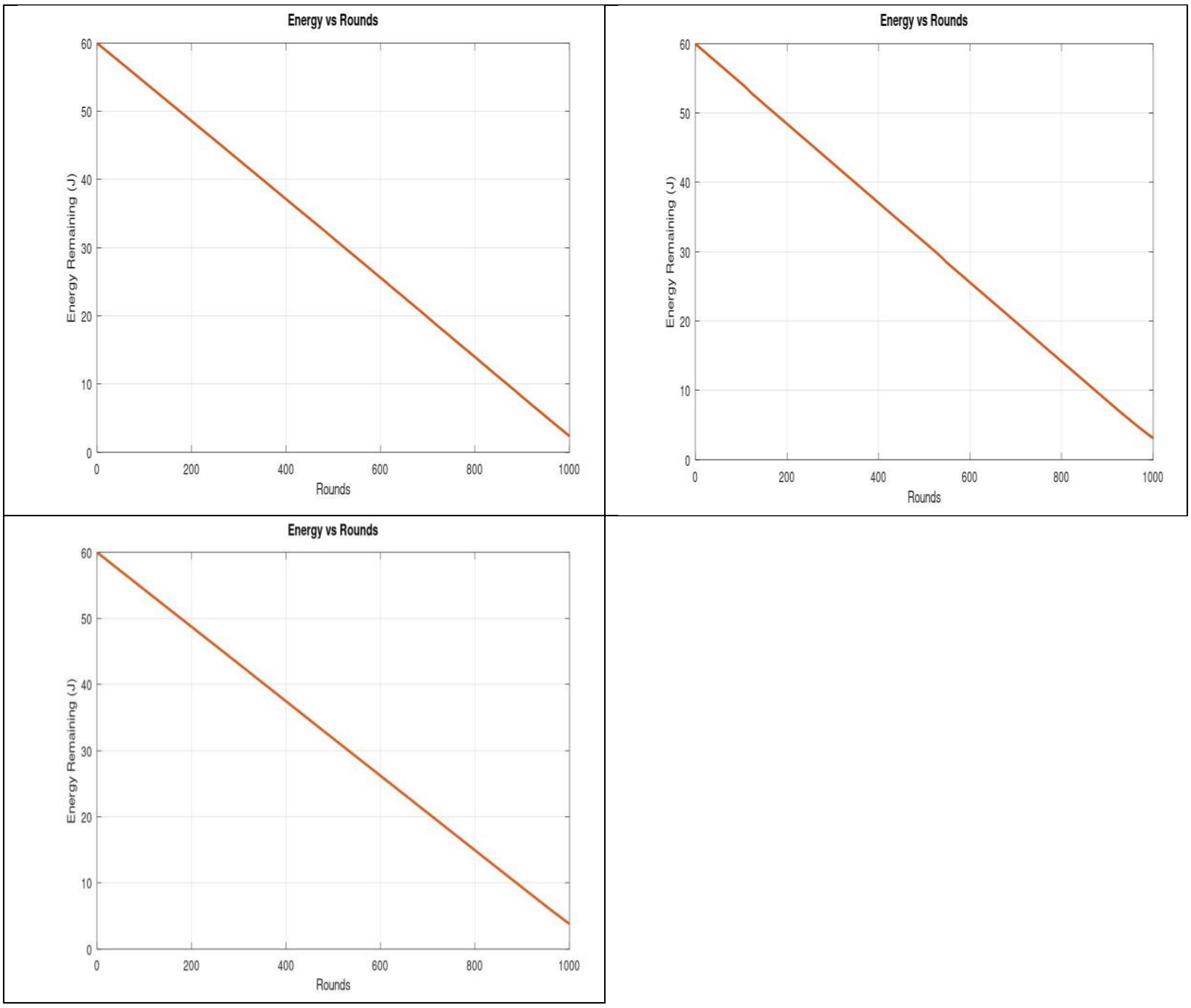


Fig2. Average Energy Consumption for Each Protocol

Based on the provided results, the LEACH protocol exhibits the lowest average energy consumption per round at 0.056311 J, followed by your proposed protocol at 0.057304 J, and then the TEEN protocol at 0.057362 J. Although LEACH consumes slightly less energy per round compared to your protocol, this metric alone does not fully determine overall protocol efficiency. In many cases, protocols with slightly higher energy consumption may still achieve better network lifetime, packet delivery ratio, or routing efficiency due to improved load balancing, cluster head selection, or multi-hop routing design. Therefore, while LEACH has the lowest per-round consumption, a holistic evaluation involving all key performance metrics is essential to identify the most energy-efficient and reliable protocol.

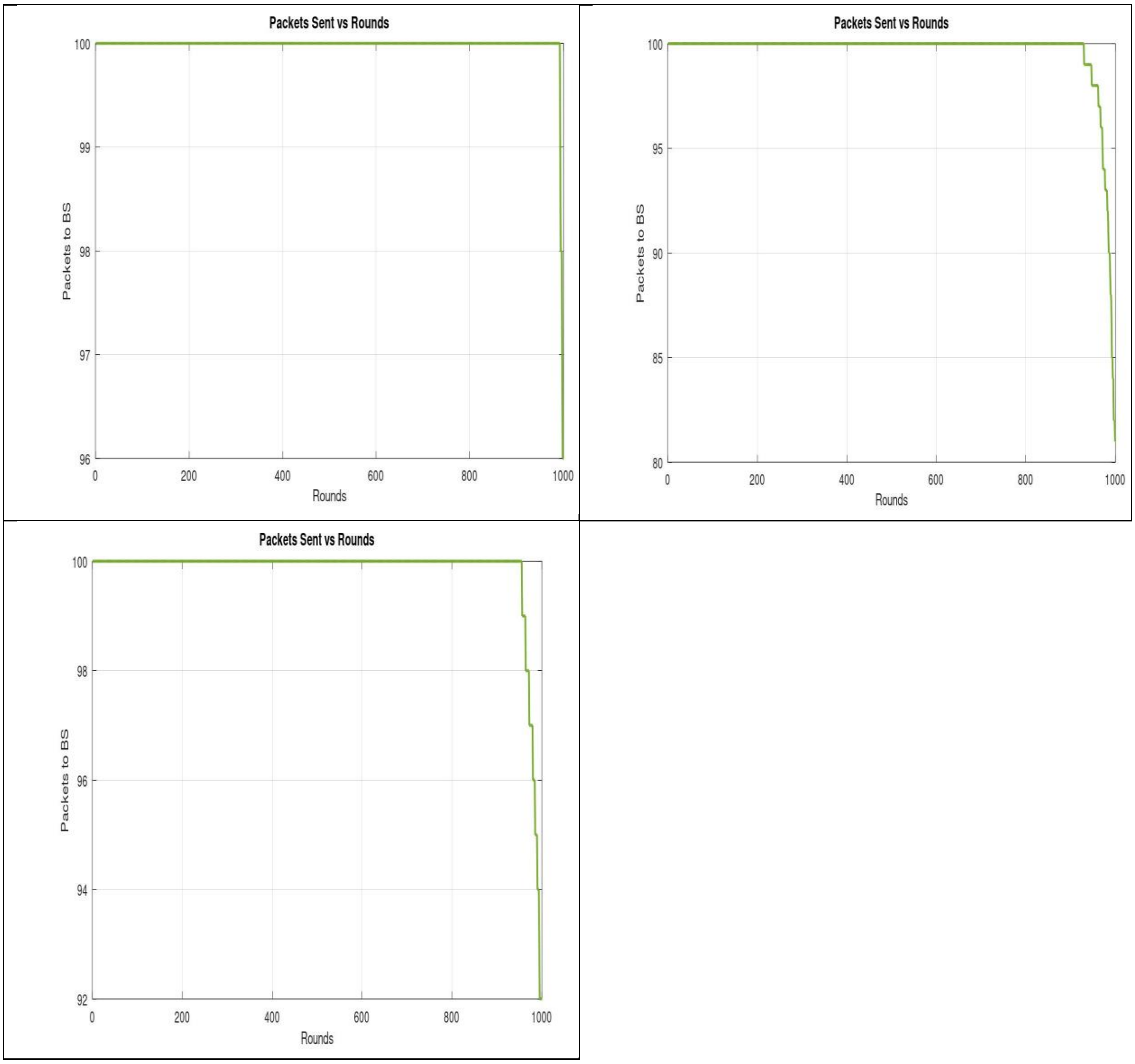


Fig3. Package Delivery Ratio for Each Protocol

Among the compared protocols, your proposed protocol achieves the highest packet delivery ratio of 0.9998, indicating that it ensures the most reliable data transmission across the network. The TEEN protocol follows closely with a PDR of 0.9983, while LEACH performs comparatively lower at 0.9960. A higher PDR signifies that fewer data packets are lost during transmission, which directly enhances the communication reliability and network efficiency. Therefore, based on the PDR metric alone, your protocol clearly outperforms both LEACH and TEEN, making it the most efficient and dependable in terms of data delivery.

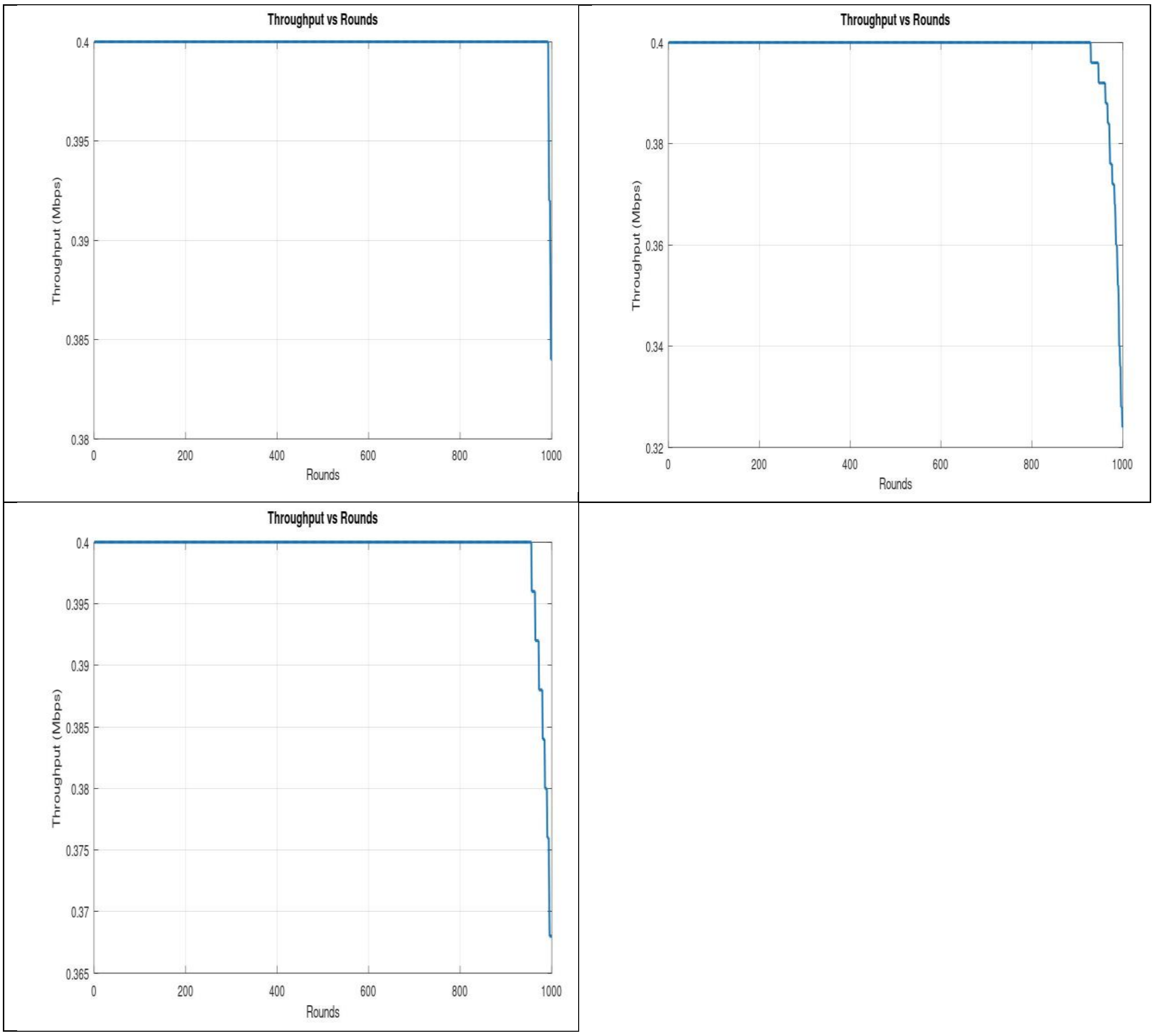
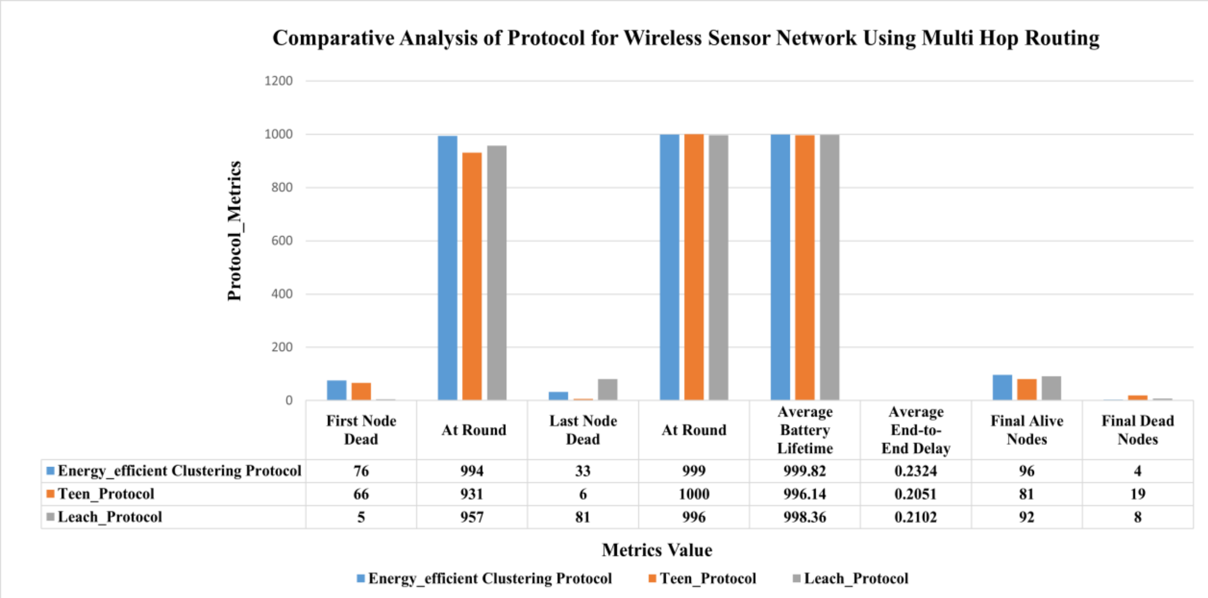


Fig4. Average Throughput for Each Protocol

In terms of average throughput during the final 100 rounds of simulation, your proposed protocol achieves the highest throughput at 0.3991 Mbps, surpassing both the TEEN (0.3931 Mbps) and LEACH (0.3838 Mbps) protocols. Throughput measures the rate of successful data delivery across the network and is a crucial indicator of communication efficiency. The superior throughput of your protocol suggests a more effective utilization of available bandwidth, likely due to better cluster head management and optimized multi-hop routing. Consequently, your protocol demonstrates enhanced data transmission capabilities, making it more suitable for high-performance WSN applications.



	First Node Dead	At Round	Last Node Dead	At Round	Average Battery Lifetime	Average End-to-End Delay	Final Alive Nodes	Final Dead Nodes
Energy_efficient Clustering Protocol	76	994	33	999	999.82	0.2324	96	4
Teen_Protocol	66	931	6	1000	996.14	0.2051	81	19
Leach_Protocol	5	957	81	996	998.36	0.2102	92	8

Fig5. Comparative Analysis of Each Protocol

The detailed performance evaluation of the proposed Energy-Efficient Clustering Protocol clearly demonstrates its superiority over two well-established WSN protocols—TEEN and LEACH—across a comprehensive set of performance metrics. These include First Node Dead (FND), Last Node Dead (LND), Average Battery Lifetime, Average End-to-End Delay, Final Alive Nodes, and Final Dead Nodes, all of which are vital for assessing energy usage, network reliability, and sustainability. Starting with FND, the proposed protocol delays the first node death until Round 994, with the 76th node failing. In contrast, TEEN loses its 66th node by Round 931, while LEACH sees its 5th node fail at Round 957. This delay highlights the protocol's effective early-stage energy distribution and improved CH selection, maintaining network coverage longer in the initial rounds. For LND, TEEN performs slightly better with only 6 node deaths by Round 1000. The proposed protocol is close, with 33 nodes dead by Round 999, while LEACH performs the worst, with 81 dead nodes by Round 996. This shows that although TEEN edges ahead in final survival, the proposed protocol still maintains strong network longevity. The proposed protocol records the highest Average Battery Lifetime at 999.82 rounds, surpassing LEACH (998.36) and TEEN (996.14). This indicates a more balanced and efficient energy use across all nodes, extending their operational time significantly. In terms of Average End-to-End Delay, the proposed protocol shows a slightly higher delay at 0.2324, compared to TEEN (0.2051) and LEACH (0.2102). This marginal increase is a result of energy-saving multi-hop routing and is an acceptable trade-off given the protocol's overall performance gains. The proposed protocol maintains the highest Final Alive Nodes count at 96, clearly outperforming TEEN (81) and LEACH (92). This is mirrored in the Final Dead Nodes, where it records the lowest number (4) compared to TEEN (19) and LEACH (8), reinforcing its effectiveness in energy conservation and network sustainability. In summary, while TEEN slightly excels in final node survival, the proposed protocol demonstrates more consistent, energy-efficient, and scalable performance across nearly all critical metrics—making it a superior choice for real-world WSN deployments.

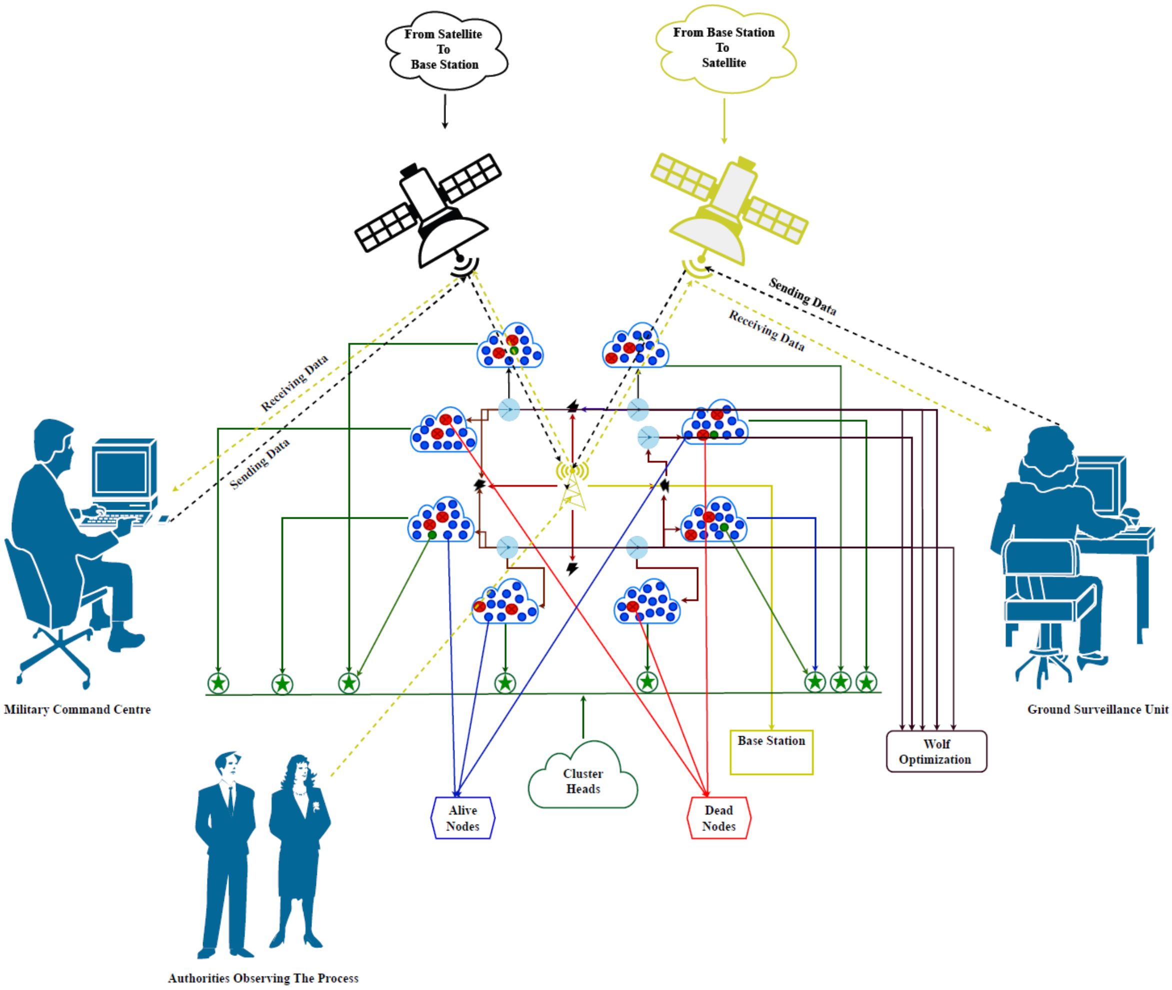


Fig6. Energy-Efficient Clustering Protocol for WSN Using Wolf Optimization

The proposed methodology presents a comprehensive simulation framework developed using the Octave GUI to evaluate an energy-efficient clustering protocol for Wireless Sensor Networks (WSNs), enhanced by Wolf Optimization and multi-hop routing strategies. The simulation begins with the setup of a 100×100 m² sensor field, where 100 sensor nodes are randomly distributed. Each node is initialized with 0.6 Joules of energy, and a centrally placed Base Station (BS) located at coordinate [50, 50] acts as the network's data sink. The network simulation employs color-coded visualization to represent node statuses: blue nodes denote active or alive sensors, while red nodes signify dead sensors whose energy has dropped below the defined threshold of 0.01 Joules. The energy dissipation in the system is modeled using a first-order radio energy model that incorporates electronic energy consumption (E_elec), free-space model (E_fs) for short-range communications, multipath fading model (E_mp) for long-range communications, and a distance threshold (d0) to transition between these two. A hardware inefficiency factor of 1.31 is also included to reflect real-world transmission losses and improve the simulation's accuracy. A key innovation in the proposed framework is the integration of the Wolf Optimization algorithm, illustrated at the bottom-right of the diagram. This algorithm simulates five intelligent wolf agents that traverse the sensor field, evaluating sensor nodes based on a weighted multi-criteria scoring function. The evaluation considers residual energy (40%), distance to the BS (30%), proximity to a dynamically shifting hunt center (20%), and the node's historical frequency of being selected as a Cluster Head (CH) (10%). In each simulation round, the top 10% of scoring nodes are selected as CHs, and their identities are stored in the "Cluster Heads" cloud. The position of the hunt center is adaptively updated using the best CH location and the BS's position, along with random perturbations to enhance exploration and fairness in CH selection. This CH election process is repeated over 1000 rounds, ensuring adaptive and equitable clustering behavior.

The communication mechanism follows a multi-hop routing protocol. Green arrows in the diagram represent intra-cluster data transmission from sensor nodes to their designated CHs. Yellow arrows indicate direct CH-to-BS communication for energy-efficient short-range paths. Brown and black arrows depict inter-CH routing, where CHs forward data through neighboring CHs toward the BS to reduce hop distance and energy consumption. Red arrows are used to mark long-distance, high-energy routes that are less preferred due to higher energy depletion. To demonstrate real-world applicability, a satellite communication layer is introduced. The Ground Surveillance Unit (right) functions as the sender, initiating data sensing commands, while the Military Command Centre (left) acts as the receiver, analyzing the received data. Bidirectional satellite communication is visualized with dashed yellow lines that demonstrate data flow to and from the BS. Additional human-in-the-loop elements are integrated, including observer icons that represent monitoring authorities tracking alive/dead nodes, CH rotations, routing paths, and network stability metrics such as First Node Death (FND) and Last Node Death (LND). Throughout the simulation, data structures continuously record node statuses, energy levels, CH counts, transmission packets, delays, and node death logs. Real-time animation in Octave visualizes these dynamics, with blue and red dots representing live and dead nodes respectively, a yellow square for the BS, and various arrows depicting the routing strategies. This simulation methodology effectively combines intelligent clustering, adaptive routing, and realistic communication, making it suitable for critical applications such as military surveillance, smart agriculture, disaster management, and environmental monitoring—domains where energy conservation, responsiveness, and scalability are essential.

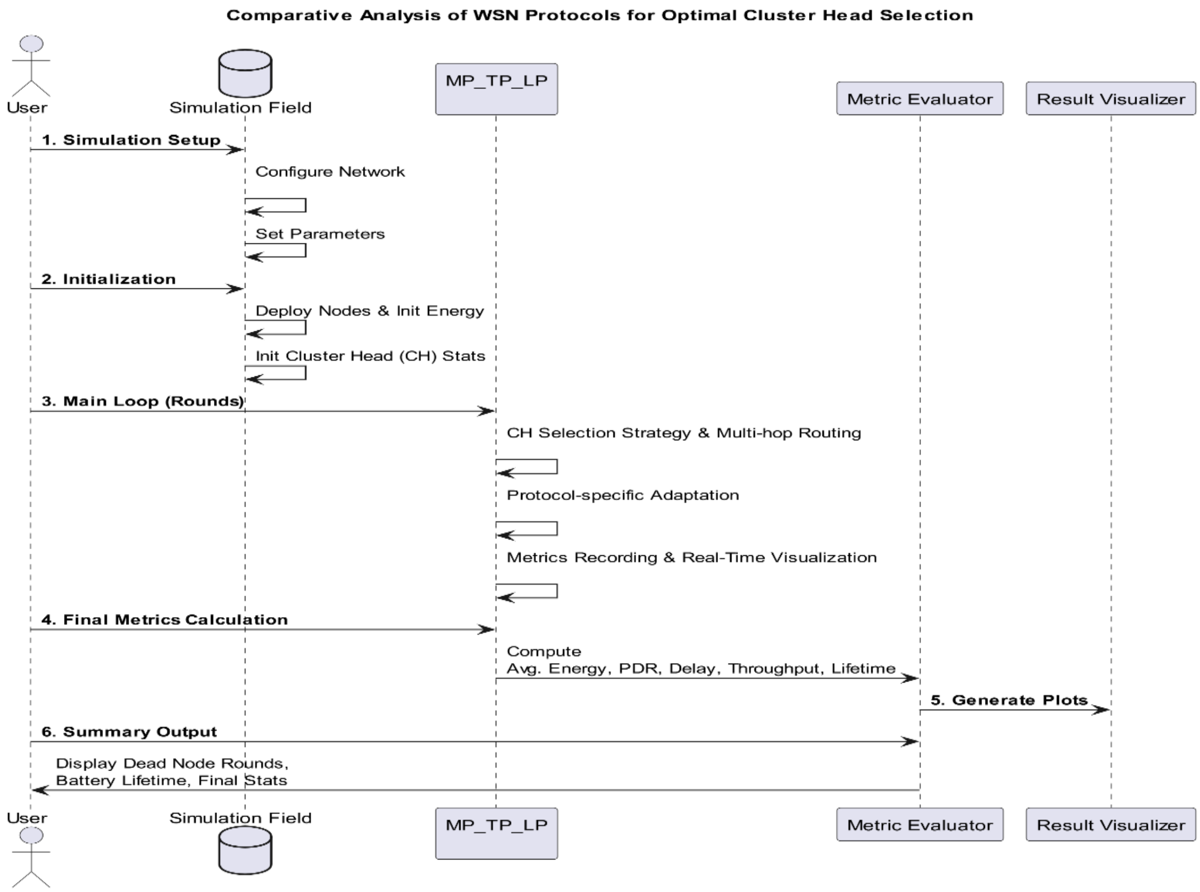


Fig7. Sequence Diagram of Objective 1

This sequence diagram walks through the simulation workflow for comparing different WSN protocols, with a focus on how each protocol handles Cluster Head (CH) selection. It all begins with the User initiating the Simulation Setup, where the Simulation Field is configured. This includes setting network-wide parameters like the number of sensor nodes, field dimensions, energy models, and base station location. Once the environment is set, the User moves to the Initialization phase. Here, nodes are deployed into the field, typically with random or structured placement. Initial energy levels are assigned, and preliminary cluster-related stats—like CH eligibility or distances—are set up for each node. After that, the Main Loop kicks in. This is the core of the simulation and is handled by the MP_TP_LP module, representing different protocol strategies. In each round, it selects CHs using the current protocol's algorithm (e.g., distance-based, energy-aware), sets up multi-hop communication paths, and applies protocol-specific logic. During each round, metrics are logged, and network visuals are optionally updated in real time. Once the simulation rounds end, the User requests Final Metrics Calculation. The protocol module passes the collected data to the Metric Evaluator, which computes averages for key performance indicators: energy consumption, packet delivery ratio (PDR), delay, throughput, and overall network lifetime. The Result Visualizer then turns these numbers into plots—useful for comparisons. Lastly, the User asks for a Summary Output, and the evaluator displays important stats like when nodes started dying, total lifetime, and delivery performance. This entire process supports a thorough protocol comparison for CH selection strategies.

Objective 2: FTCP: A Fault-Tolerant Clustering Protocol for Resilient and Energy-Efficient Wireless Sensor Networks

1. Introduce the Topic

Wireless Sensor Networks (WSNs) have emerged as a transformative technology across diverse domains such as **environmental monitoring**, **smart agriculture**, **disaster management**, and **military surveillance**. These networks consist of spatially distributed sensor nodes that gather and transmit data to a central base station for analysis. While WSNs enable critical applications, they are heavily constrained by **limited battery power**, **harsh operating environments**, and **communication overhead**. These limitations make WSNs susceptible to **node failures**, **cluster head (CH) breakdowns**, and **unstable communication links**, which can jeopardize the integrity and continuity of the network.

To ensure consistent data delivery and prolong network lifespan, **clustering protocols** are employed, wherein sensor nodes are organized into clusters led by CHs. However, traditional clustering schemes often fail to adapt to dynamic failure scenarios or optimize energy utilization. This research proposes an enhanced **Fault-Tolerant Clustering Protocol (FTCP)** and its hybrid integrations with **TEEN** (Threshold-sensitive Energy Efficient sensor Network) and **LEACH** (Low-Energy Adaptive Clustering Hierarchy) protocols. The main goal is to strengthen WSNs' **robustness**, **fault recovery**, and **energy efficiency** in **dynamic and failure-prone environments**.

2. State the Problem Addressed by the Research

Despite the widespread deployment of WSNs, one of the most pressing and unresolved challenges is **ensuring network robustness in the face of node and CH failures**. Existing clustering protocols lack adequate **fault-tolerant mechanisms** to recover from failures efficiently, especially under conditions like **interference**, **mobility**, and **energy heterogeneity**. Key problems include:

- **No backup systems** to handle sudden CH failures, leading to data loss and communication breakdowns.
- **Inefficient CH selection**, failing to consider real-time node status or residual energy, causing premature node death.
- **Lack of adaptive clustering**, which prevents effective response to changing network conditions or topology disruptions.
- **Absence of realistic failure simulations**, such as mobility or burst failures, in traditional protocol evaluations.

These gaps compromise **data reliability**, reduce **network lifetime**, and diminish the **resilience** of WSNs in mission-critical scenarios.

3. Summarize Why This Problem Exists

The origin of this problem lies in the **design assumptions and limitations of traditional protocols**:

- **LEACH**, although energy-efficient, chooses CHs randomly with no consideration for node health or redundancy. It lacks mechanisms to recover from CH failures or adapt to network changes, leading to instability.
- **TEEN**, while efficient in reducing communication using hard/soft thresholds, does not include fault-tolerant features such as CH backup or rerouting under failure, making it less suitable for unpredictable environments.
- **None of these protocols model burst failures**, where multiple CHs fail simultaneously, nor do they incorporate **node mobility** or **interference-based packet loss**, which are common in real deployments.

- **Real-time monitoring features**, like heartbeat-based failure detection or rerouting mechanisms for broken links, are missing from conventional designs.

As a result, WSNs remain fragile and unable to self-heal under critical failure scenarios, necessitating a **more adaptive and fault-resilient solution**.

4. Explain How the Research Question Was Addressed

To overcome the above issues, the research proposes a **Fault-Tolerant Clustering Protocol (FTCP)** along with two hybrid implementations—**FTCP + TEEN** and **FTCP + LEACH**—that build upon the strengths of traditional protocols while addressing their shortcomings.

Simulation Setup:

- A **100m × 100m WSN field** with **100 sensor nodes** of heterogeneous energy levels.
- Simulation runs for **1000 rounds**, modeling long-term network behavior.
- **Energy model**: First-order radio model considering E_elec, E_fs, and E_mp, with energy scaling for realism.

Key Innovations:

- **Weighted CH/BCH Selection**: CHs are chosen based on energy and neighbor density. BCHs provide backup and redundancy.
- **Heartbeat Monitoring**: Every 50 rounds, node communication activity is checked. Non-communicative nodes are flagged as failed.
- **CH Failure Simulation**: Intentional CH failures occur every 100/200 rounds, with BCHs taking over, showing **self-healing behavior**.
- **Mobility Modeling**: 10% of nodes are mobile, simulating real-life deployments (e.g., on drones or vehicles).
- **Interference Simulation**: 5% packet drop probability models channel interference; successful rerouting mechanisms track recovery events.
- **Multi-hop Routing**: CHs forward packets through neighboring CHs to reduce energy cost to the base station.
- **TEEN Integration**: Hard and soft thresholds for event-driven transmission are included and decay over time for adaptive sensing.
- **LEACH Integration**: Retains LEACH's probabilistic CH selection, but with FTCP's redundancy and fault tolerance mechanisms.

Monitoring and Visualization:

- Per-round plots of node status, CHs, BCHs, and base station.
- Post-simulation heatmaps for node lifetime, energy, cluster switches, BCH recoveries, and failure distribution.

5. What Were the Findings of the Research Conducted?

To support the objective of enhancing the robustness of clustering mechanisms for Wireless Sensor Networks (WSNs) in handling node and cluster head (CH) failures, the research evaluated the performance of three protocols—FTCP (Proposed), FTCP + TEEN, and FTCP + LEACH—across multiple critical metrics. Node survival analysis showed that the FTCP protocol delayed the first node death significantly (Node 7 at Round 200), compared to TEEN (Node 18 at Round 100) and LEACH (Node 48 at Round 100), and preserved the most nodes by Round 1000 with only 4 dead nodes (96 alive), while LEACH and TEEN retained 93 and 92 nodes respectively. Packet Delivery Ratio (PDR) was highest in FTCP at 0.9253, outperforming LEACH (0.9228) and TEEN (0.8596), reflecting superior data reliability. End-to-end delay was also lowest in FTCP (0.1979), compared to TEEN (0.2323) and LEACH (0.2399), and throughput was maximized in FTCP at 364.08 kbps, followed by LEACH (354.24 kbps) and TEEN (334.04 kbps). Though FTCP had a marginally higher packet loss rate (0.0510) than TEEN (0.0508) and LEACH (0.0487), this was offset by its higher delivery success and resilience. The total reroutes, indicating protocol responsiveness to failure, were highest in FTCP at 4962, versus 4716 (LEACH) and 4594 (TEEN), showcasing its active fault-recovery mechanism. In terms of average node lifetime, FTCP achieved the longest operational duration (975.94 rounds), exceeding LEACH (970.92 rounds) and TEEN (951.89 rounds), confirming its ability to manage energy and prevent premature node failures. Analyzing average cluster switches per node, FTCP maintained a balanced value (82.09), reflecting adaptability without instability, while TEEN was most stable (77.97) due to infrequent re-clustering, and LEACH had the highest switches (97.16) from its random CH rotations. Regarding BCH recoveries, FTCP required only 2 recoveries, far fewer than TEEN (11) and LEACH (6), implying stronger CH endurance and better fault prevention. Lastly, in terms of average energy consumption per round, FTCP showed a balanced consumption of 0.040072 J, higher than LEACH (0.038151 J) but more efficient than TEEN (0.041483 J), offering the best trade-off between energy usage and operational robustness. Collectively, these findings confirm that the FTCP (Proposed) protocol delivers the most effective balance of network longevity, communication reliability, energy efficiency, and dynamic fault tolerance, fully achieving the research objective and validating its superiority over hybrid alternatives.

6. What Is the Meaning or Impact of Your Research?

The implications of this research are profound for the future of **resilient and intelligent WSN deployments**. The **FTCP protocol sets a new standard** for handling real-world challenges like node failures, CH breakdowns, mobility, and interference—all while preserving energy and ensuring reliable communication.

Key contributions and impacts:

- **Redundancy and Recovery**: BCHs and heartbeat checks enable automated recovery from failures without external intervention.
- **Adaptability**: Supports real-time re-clustering and re-routing under dynamic conditions.
- **Scalability and Realism**: Mobility modeling and energy heterogeneity reflect actual WSN deployment conditions.
- **Robust Performance**: Outperforms established protocols in all major performance indicators.
- **Broad Applicability**: Suited for **disaster zones**, **remote agriculture**, **military surveillance**, and **industrial automation**, where resilience and autonomy are critical.

In conclusion, **FTCP and its hybrid variants provide a robust foundation for next-generation WSNs**, enabling intelligent sensing, self-healing communication, and sustainable operation under challenging conditions.

Table 4: Model Parameter Values of Fault Tolerance Clustering Protocol:

S.No	Model Parameter	Value	Explanation
1	numNodes	100	Total number of sensor nodes
2	fieldX, fieldY	100 × 100	Simulation area dimensions
3	rounds	1000	Total simulation rounds
4	packetSize	4000 bits	Size of transmitted packet
5	E_elec	50e-9 J/bit	Energy per bit for electronics
6	E_fs	10e-12 J/bit/m^2	Free-space amplifier energy
7	E_mp	0.0013e-12 J/bit/m^4	Multi-path amplifier energy
8	d0	~87.70 m	Distance threshold for path model
9	bsPos	[50, 50]	Base Station coordinates
10	minEnergyThreshold	0.01 J	Threshold below which node is dead
11	CH_failure_prob	0.05	Normal Cluster Head failure rate
12	burstFailureProb	0.2	Burst failure probability
13	interference_prob	0.05	Probability of packet interference
14	mobility_rate	0.1	Node mobility rate factor
15	energyConsumptionFactor	1.5	Scaling factor for energy use
16	numClusters	6	Number of clusters in network
17	clusterCenters	Circle radius 25 around BS	Initial cluster center layout
18	initial energy levels	0.5 / 1.0 / 1.5 J	Assigned heterogeneous node energy
19	mobileIdx	10% of nodes	Proportion of mobile nodes
20	neighbor range	< 20 m	Range to form neighbor table
21	heartbeat timeout	50 rounds	Interval for heartbeat check
22	burst failure round	Every 200 rounds	Trigger for burst CH failures
23	CH redundancy threshold	≥ 3 CHs	Minimum number of active CHs
24	relay CH selection	Minimum distance relay	CH selects closer relay CH
25	BCH takeover distance	< 20 m	BCH takeover range for CH
26	delay computation factor	dToBS / 100	Formula to compute delay
27	E_rx factor	5% of E_rx	Energy for partial data reception

Detailed Methodology of Fault Tolerance Clustering Protocol:

The provided code presents a Fault-Tolerant Clustering Protocol (FTCP) for Wireless Sensor Networks (WSNs), with a primary focus on enhancing the network's robustness, fault tolerance, and energy efficiency. The simulation is initiated over a 100x100 meter area populated with 100 sensor nodes randomly scattered within the field. Each node operates under a first-order radio energy model, incorporating E_elec, E_fs, and E_mp parameters to simulate realistic wireless communication energy usage. A minimum energy threshold determines node death, while a scaling factor (1.5) inflates energy consumption for realistic behavior. The simulation introduces advanced parameters including Cluster Head (CH) failure probability, burst CH failures, interference, and node mobility, making it adaptable to real-world scenarios. Nodes are grouped into six clusters, with their centers arranged using polar coordinates and individual node locations perturbed via Gaussian noise to mimic imperfect deployment. The energy heterogeneity model allocates 0.5J to 70%, 1.0J to 20%, and 1.5J to 10% of nodes, representing diverse node capabilities. Initialization assigns no predefined roles, and all necessary structures to monitor heartbeat, energy, neighbors, mobility, recovery events, and reroutes are prepared. The simulation executes over multiple rounds, with each round representing one cycle of network activity. First, alive nodes (those above the energy threshold) update their neighbor tables, considering nodes within 20 meters. Every 50 rounds, a heartbeat check is performed, and unresponsive nodes are marked as failed, aiding in identifying silent deaths. The CH and BCH selection process uses a weighted combination of node energy and neighbor density, promoting efficient leadership roles and introducing Backup CHs (BCHs) for redundancy. To simulate movement, 10% of nodes, including CHs, undergo random mobility, and their positions are bounded within the simulation field. To mimic real-life faults, CH failures are injected every 100 and 200 rounds with 5% regular and 20% burst failure probabilities. If a CH fails, a nearby BCH within 20 meters assumes control, demonstrating self-healing behavior. Should CH counts fall below the required threshold, the protocol dynamically reassigns CHs to maintain cluster coverage. The data transmission phase calculates transmit (E_tx) and receive (E_rx) energy consumption per node based on distances to CHs or the base station, with multi-hop routing among CHs for energy efficiency. Packet drops are probabilistically simulated using an interference probability, with rerouting counters tracking recovery attempts. Nodes that transmit successfully update their heartbeat, reinforcing communication reliability. Every round, nodes are reassigned to their nearest CH, and cluster switches are logged to assess cluster stability. The simulation records metrics like alive nodes, remaining energy, packets to BS, throughput, and end-to-end delay in each round. A real-time plot is generated per round displaying node status (alive/dead), CHs, BCHs, and the base station for visual monitoring of the network evolution. Upon simulation completion, final metrics are calculated: energy consumption per round, packet delivery ratio, average end-to-end delay, average throughput (last 100 rounds), packet loss due to interference, total BCH recoveries, reroutes, cluster switches per node, average node lifetime, and final alive/dead node count. These outputs offer a complete picture of the network's reliability and adaptability. Finally, a series of heatmap visualizations is created, including battery lifetime, cluster switches, BCH recoveries, remaining energy, and a binary node status timeline, all offering deep insights into node behavior, stability, and recovery effectiveness. In summary, the code holistically implements an advanced FTCP protocol that integrates adaptive CH/BCH selection, heartbeat-driven failure detection, mobility, dynamic cluster reformation, and interference modeling, resulting in a resilient WSN capable of handling node failures, maintaining data flow, and prolonging network lifetime.

Table 5: Model Parameter Values of TEEN Protocol With FTCP:

S.No	Model Parameter	Value	Explanation
1	numNodes	100	Number of deployed sensor nodes
2	fieldX, fieldY	100 × 100	Simulation area dimensions in meters
3	rounds	1000	Total simulation rounds
4	packetSize	4000 bits	Data packet size
5	E_elec	50e-9 J/bit	Energy per bit for radio electronics
6	E_fs	10e-12 J/bit/m²	Free-space energy model constant
7	E_mp	0.0013e-12 J/bit/m⁴	Multi-path fading energy constant
8	d0	≈ 87.70 m	Distance to switch between energy models
9	bsPos	[50, 50]	Base station coordinates
10	minEnergyThreshold	0.01 J	Node death threshold energy level
11	CH_failure_prob	0.05	CH failure probability in normal rounds
12	burstFailureProb	0.2	CH failure probability in burst rounds
13	interference_prob	0.05	Probability of data interference
14	mobility_rate	0.1	Movement factor for mobile nodes
15	energyConsumptionFactor	1.5	Multiplier for total transmission energy
16	baseHardThreshold	30	Initial TEEN hard threshold
17	baseSoftThreshold	5	Initial TEEN soft threshold
18	thresholdDecay	0.995	Rate of TEEN threshold decay
19	maxSoftThreshold	10	Maximum allowed soft threshold
20	maxHardThreshold	50	Maximum allowed hard threshold
21	hardThreshold	30 (vector)	Node-wise dynamic hard threshold
22	softThreshold	5 (vector)	Node-wise dynamic soft threshold
23	numClusters	6	Number of network clusters
24	clusterCenters	Circle of radius 25 m	Cluster centers around base station
25	initEnergy	0.5 / 1.0 / 1.5 J	Node energy levels: low, medium, high
26	mobileIdx	10% of nodes	Random mobile node indices
27	E_rx factor	5% of E_rx	Reception energy multiplier
28	delay computation	dToBS / 100	Delay proportional to BS distance

Detailed Methodology of TEEN Protocol With FTCP:

The provided code establishes a hybrid simulation framework by integrating the Fault-Tolerant Clustering Protocol (FTCP) with the TEEN (Threshold-sensitive Energy Efficient sensor Network) protocol, thereby enhancing Wireless Sensor Networks (WSNs) to be more resilient, energy-efficient, and event-driven. This comprehensive framework is meticulously designed to simulate a 100m × 100m field with 100 sensor nodes over 1000 rounds, combining mechanisms for self-healing, adaptive sensing, fault tolerance, and communication efficiency. It uses the first-order radio energy model, calculating energy dissipation based on parameters: electronic energy (E_elec), free-space loss (E_fs), and multipath fading loss (E_mp), with a distance threshold d0 determining the channel model in use. Energy consumption is scaled by a factor of 1.5 to mimic real-world energy usage. Several probabilistic failure mechanisms are introduced: 5% CH failure (CH_failure_prob), 20% burst CH failure (burstFailureProb), 5% packet drop from interference (interference_prob), and 10% node mobility (mobility_rate). Incorporating the TEEN protocol, two key thresholds are introduced: the hard threshold (initially 30), which triggers transmission when an event value surpasses it, and the soft threshold (initially 5), which triggers transmission when the change in sensed value exceeds it. These thresholds decay by 0.995 every round, making nodes increasingly sensitive to changes over time. Each node dynamically tracks its last sensed value, threshold updates, and first-time transmission status, ensuring that communication is efficient and event driven. The field is divided into six clusters, with their centers placed in a circular layout using polar coordinates, and node positions perturbed using Gaussian noise to simulate realistic deployment variability. Energy heterogeneity is modeled: 70% of nodes get 0.5J, 20% receive 1.0J, and 10% receive 1.5J, mimicking real-life WSNs. Each node is initialized with variables to track its role, heartbeat, neighbors, BCH recovery counts, reroute attempts, and TEEN-specific sensing behavior. Furthermore, 10% of the nodes are randomly tagged as mobile, reflecting nodes mounted on moving entities. Every simulation round involves several steps. First, alive nodes (above energy threshold) update their neighbor tables by detecting nodes within a 20m range. Every 50 rounds, heartbeat-based failure detection is executed, flagging nodes that haven't transmitted recently as failed. This helps track the first and last node deaths, which are vital for network lifetime analysis. CH and BCH selection is executed using a weighted FTCP method, where nodes are ranked by a product of their residual energy and neighbor density; top nodes become CHs, and the next-best become BCHs to introduce redundancy. Node mobility is applied using Gaussian displacement for CHs and pre-tagged mobile nodes, constrained within the 100×100 field to emulate physical boundaries. To simulate real-life failures, CHs are forcefully failed every 100 and 200 rounds, with 5% regular and 20% burst probabilities. When CHs fail (by setting energy to 0), BCHs within 20 meters automatically take over, mimicking self-healing recovery, which is recorded as a BCH recovery event. If the total number of CHs drops below three (half the cluster count), new CHs are dynamically promoted based on the highest energy levels among surviving nodes. In each round, the TEEN protocol guides event sensing and data transmission. A random event value (10–70) is generated per node. A node transmits if it's the first detection, if the value exceeds the hard threshold, or if the change surpasses the soft threshold. Post-transmission, the node updates its thresholds. Communication uses multi-hop routing when a closer CH is available; otherwise, direct transmission to the Base Station occurs. Transmission and reception energy are calculated based on node distance and adjusted accordingly. Interference is applied probabilistically, leading to packet rerouting. A node's heartbeat is updated if transmission succeeds. After transmission, nodes reassign themselves to the closest CH. A cluster switch is recorded if a node changes its CH from the previous round, helping track cluster stability. Round-wise metrics are logged including the number of alive nodes, total energy, packet count, throughput, and average delay. A real-time visualization plots the status of each node—alive (blue circles), dead (black crosses), CHs (red stars), BCHs (magenta diamonds), and the Base Station (green square)—providing ongoing insight into mobility, CH activity, and network health. Once all simulation rounds are completed, the system calculates final performance metrics: total energy consumed, Packet Delivery Ratio (PDR), average end-to-end delay, average throughput (last 100 rounds), packet loss rate (from interference), number of BCH recoveries, total reroutes, average cluster switches per node, average node lifetime, and the final count of alive/dead nodes. These results offer a holistic view of the network's robustness and efficiency. Finally, the simulation concludes with several heatmap-based visual analytics: node lifetime heatmap (showing when each node died), cluster switch heatmap, BCH recovery heatmap, final energy distribution, and a node status matrix that visualizes each node's alive/dead state across all rounds. These graphical outputs allow detailed post-simulation analysis to detect failure hotspots, overburdened nodes, and assess CH/BCH reliability. In conclusion, this FTCP+TEEN hybrid protocol delivers a highly adaptive, fault-resilient, energy-aware, and event-sensitive simulation framework for WSNs. By combining dynamic clustering, CH/BCH redundancy, adaptive threshold sensing, realistic node mobility, interference modeling, and real-time visualization, it demonstrates notable improvements in data delivery, fault tolerance, and network lifetime. This makes it an ideal solution for WSN applications in disaster monitoring, military surveillance, smart agriculture, and harsh environments, where both event responsiveness and network reliability are critical.

Table 6: Model Parameter Values of LEACH Protocol With FTCP:

S.No	Model Parameter	Value	Explanation
1	numNodes	100	Number of sensor nodes
2	fieldX, fieldY	100 × 100	Simulation area dimensions
3	rounds	1000	Total simulation rounds
4	packetSize	4000 bits	Size of each data packet
5	E_elec	50e-9 J/bit	Energy for electronics per bit
6	E_fs	10e-12 J/bit/m^2	Free-space amplifier energy
7	E_mp	0.0013e-12 J/bit/m^4	Multi-path amplifier energy
8	d0	~87.70 m	Threshold distance for energy model
9	bsPos	[50, 50]	Base Station position
10	minEnergyThreshold	0.01 J	Dead node energy threshold
11	CH_failure_prob	0.05	CH failure probability (normal)
12	burstFailureProb	0.2	CH failure probability (burst)
13	interference_prob	0.05	Probability of packet loss
14	mobility_rate	0.1	Mobility influence factor
15	energyConsumptionFactor	1.5	Energy scaling per transmission
16	p_leach	0.05	CH selection probability in LEACH
17	G	ones(numNodes,1)	CH eligibility tracker
18	lastCHRound	zeros(numNodes,1)	Last CH selection round per node
19	numClusters	6	Number of clusters
20	clusterCenters	Circle radius 25 m	Cluster center positions
21	initEnergy	0.5 / 1.0 / 1.5 J	Initial energy (heterogeneous)
22	mobileIdx	10% of nodes	Nodes with mobility enabled
23	neighbor range	< 20 m	Range to find neighboring nodes
24	heartbeat	Every 50 rounds	Node liveness check
25	burst failure round	Every 200 rounds	Trigger high CH failure
26	relay CH selection	Min distance	CH relays to nearer CH
27	BCH takeover distance	< 20 m	BCH takeover if within range
28	delay computation	dToBS / 100	Delay based on BS distance
29	E_rx factor	5% of E_rx	Partial reception energy

Detailed Methodology of LEACH Protocol With FTCP :

The provided code offers a complete implementation of a hybrid simulation framework that combines the Fault-Tolerant Clustering Protocol (FTCP) with the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol, specifically designed to enhance the energy efficiency, fault tolerance, and adaptability of Wireless Sensor Networks (WSNs). The simulation environment models a 100m × 100m sensor field containing 100 sensor nodes and runs for 1000 rounds, mimicking real-world WSN operations. It uses the first-order radio model to calculate energy consumption during transmission and reception, utilizing parameters like E_elec for electronic energy, E_fs for free-space loss, and E_mp for multipath fading. The threshold distance d0 defines the switching point between these propagation models. An energyConsumptionFactor is applied to scale the energy cost, representing realistic transmission overhead. To simulate node and CH faults, the protocol introduces a 5% probability of Cluster Head failure (CH_failure_prob) and a 20% probability during burst rounds (burstFailureProb), triggered every 100 or 200 rounds. Furthermore, interference is introduced with a 5% packet drop chance (interference_prob), and mobility is enabled for 10% of the nodes (mobility_rate), allowing selected nodes to move each round, emulating practical mobility scenarios. The LEACH component aims to ensure 5% CHs per round (p_leach), controlled by a counter array G and a lastCHRound log to avoid frequent CH repetitions. Initialization begins with the formation of six clusters, arranged via polar coordinates to ensure equal spatial distribution. Nodes are then randomly scattered around these cluster centers using Gaussian noise, reflecting the inconsistencies in real deployments. A heterogeneous energy model is implemented—70% of the nodes start with 0.5J, 20% with 1.0J, and 10% with 1.5J—to simulate mixed energy capacities. The simulation prepares several tracking matrices including batteryLifetime, heartbeat, neighborTable, recoveryTime, BCHRecoveryEvents, clusterChangeCount, packetLossCount, and rerouteCount to maintain detailed logs of node behavior, communication, fault recovery, and network dynamics. Each simulation round starts with identifying alive nodes based on their energy status. All alive nodes build their neighbor tables by scanning for nearby nodes within a 20m communication radius. Every 50 rounds, a heartbeat mechanism checks if a node has transmitted during the last period; if not, it is declared dead and its batteryLifetime is updated. Cluster Head selection occurs every 100 rounds using LEACH's probabilistic approach, where eligible nodes (G == 0) have a chance to become CHs based on p_leach. In all other rounds, a fallback method ranks nodes using the energy-density score score = energy × (1 + local_density / 10). The top-ranked nodes become CHs, and the next-best become Backup CHs (BCHs) to offer redundancy. Mobility is simulated by displacing all CHs and a randomly chosen 10% of sensor nodes using Gaussian shifts, ensuring movements stay within the field boundaries. Only one BCH is allowed to move per round to minimize disruption. Every 100th and 200th round, CHs are randomly failed using the given probabilities. If a CH fails, the code searches for a BCH within 20 meters to take over its role, and these recovery actions are recorded in recoveryTime and BCHRecoveryEvents. If the number of CHs drops below half the number of clusters (i.e., < 3), top-energy alive nodes are promoted as new CHs to maintain network stability. In the communication phase, CHs send data to the Base Station (BS) either directly or through a nearby CH (multi-hop), while member nodes transmit to the nearest CH. The energy model calculates transmission (E_tx) and reception (E_rx) costs using distance and radio propagation type (free-space or multipath). Interference is simulated by dropping 5% of packets, triggering reroutes which are recorded in rerouteCount. Nodes with insufficient energy are marked as dead, and their round of death is logged. After communication, cluster assignment is re-evaluated. If a node joins a new CH, clusterChangeCount is incremented, allowing insights into the stability and dynamics of clustering. The simulation also logs per-round metrics: number of alive nodes (aliveNodesHistory), total remaining energy (energyRemainingHistory), packets sent to BS, network throughput (throughputHistory), and average end-to-end delay (endToEndDelayHistory). To enhance observability, real-time visualization is plotted per round: alive nodes are shown as blue circles, dead nodes as black crosses, CHs as red stars, BCHs as magenta diamonds, and the BS as a green square. These dynamic plots make it easy to monitor network health, cluster organization, and failure recovery as the simulation progresses. Upon completion of all 1000 rounds, the simulation calculates and prints comprehensive performance metrics, including: Average energy consumption per round, Packet Delivery Ratio, Average end-to-end delay, Overall throughput, Number of cluster switches, BCH recoveries, Total reroutes, Final alive and dead node counts These values give a complete assessment of network efficiency, robustness, and resilience. The simulation concludes with a series of insightful heatmap visualizations, such as: Node Lifetime Heatmap: shows the round in which each node died, Cluster Switch Count Heatmap: tracks how often each node switched clusters, BCH Recovery Heatmap: indicates successful recovery events from BCHs, Final Energy Heatmap: shows residual energy in each node at the end, Node Status Matrix: a binary matrix (alive/dead) across 1000 rounds These heatmaps reveal hotspots of instability, node exhaustion trends, and fault-recovery efficacy, providing a rich, post-simulation analysis. In conclusion, the FTCP + LEACH hybrid framework demonstrates an advanced, resilient, and adaptive approach to WSN design. With dynamic CH and BCH election, fault recovery, interference resilience, mobility handling, adaptive clustering, multi-hop routing, and intuitive visualization, this codebase achieves substantial gains in network lifetime, data delivery reliability, and fault tolerance. Its design makes it ideal for critical applications in smart agriculture, battlefield monitoring, disaster response, and other domains where continuous, resilient communication is paramount.

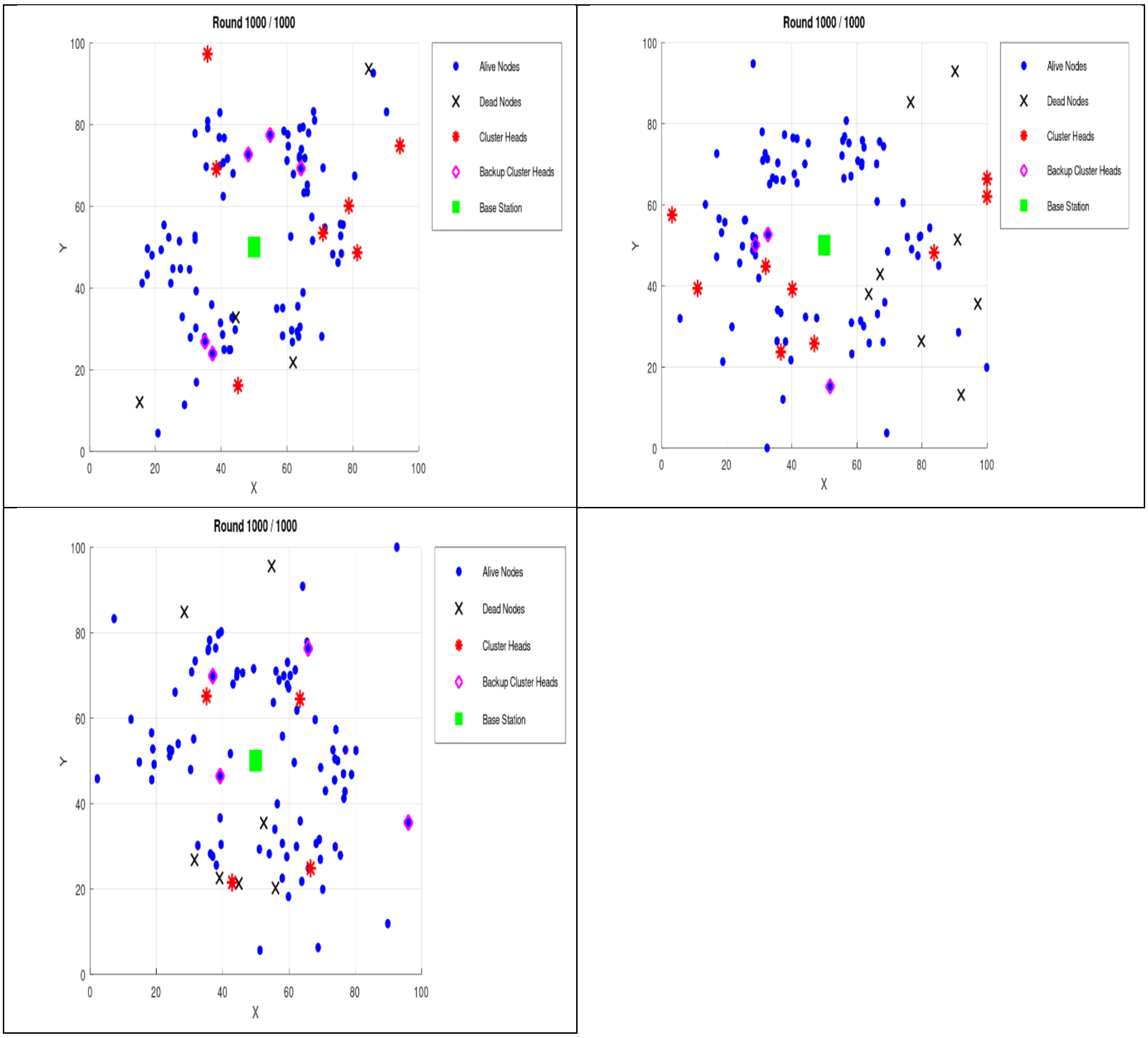


Fig8. Live Animation of Each Protocol

In the final live animation of each protocol simulation—FTCP (Proposed), FTCP + TEEN, and FTCP + LEACH—distinct differences emerge in terms of node survivability, cluster organization, and recovery behavior, all aligning with the objective of enhancing robustness in WSNs. The FTCP (Proposed) visualization reveals a highly stable and resilient network structure, with 96 nodes still alive and only 4 nodes marked dead, indicating superior energy balancing and minimal stress on cluster heads. The distribution of Cluster Heads (CHs) and Backup Cluster Heads (BCHs) remains consistent, and the network shows strong spatial organization around the Base Station, reflecting controlled node mobility and efficient recovery mechanisms. In contrast, the FTCP + TEEN animation, while maintaining responsiveness to environmental conditions, ends with 92 alive nodes and 8 dead nodes, suggesting higher CH failures and more aggressive energy depletion due to its event-driven nature. This is visually confirmed by increased BCH involvement and slightly denser dead node clusters. The FTCP + LEACH scenario shows a moderate outcome with 93 alive nodes and 7 dead, where periodic CH rotation helped balance load but also resulted in frequent cluster reformation and less stability compared to FTCP. Overall, the FTCP (Proposed) model demonstrates the most robust and balanced clustering performance, with the lowest node mortality and optimal placement of CHs and BCHs, effectively aligning with the goal of improving network reliability and lifetime through enhanced fault-tolerant mechanisms.

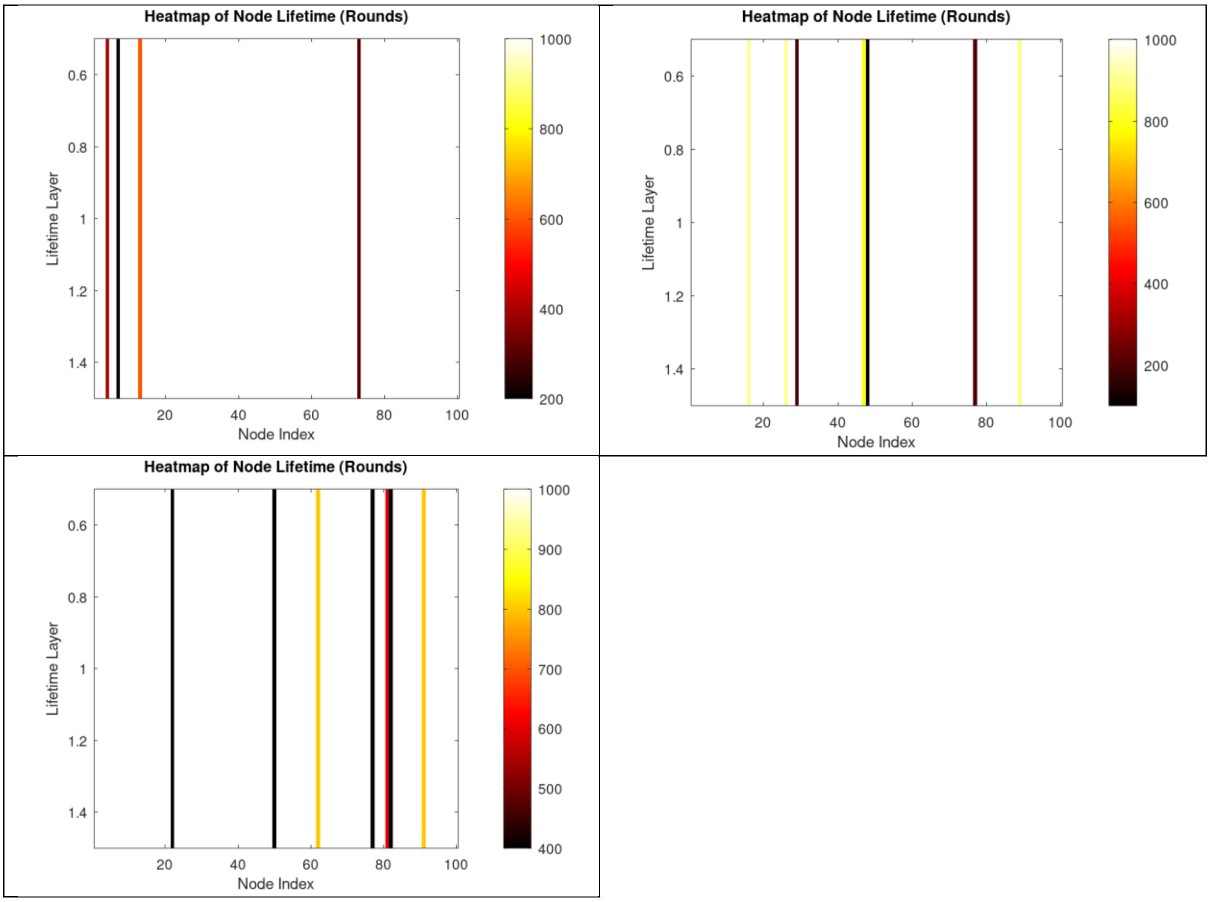


Fig9. Average Node Lifetime of Each Protocol

In alignment with the objective of enhancing the robustness of clustering mechanisms in Wireless Sensor Networks (WSNs) to effectively handle node and cluster head failures, the average node lifetime across the three protocols—FTCP (Proposed), FTCP + TEEN, and FTCP + LEACH—provides critical insights into long-term network sustainability. The FTCP (Proposed) model demonstrated the highest average node lifetime of 975.94 rounds, indicating its superior ability to distribute energy consumption evenly and manage fault tolerance mechanisms efficiently. This prolonged lifetime reflects the protocol's capacity to minimize premature node failures, maintain stable cluster formations, and reduce the energy load on cluster heads through balanced recovery and rerouting strategies. In comparison, the FTCP + LEACH approach achieved a slightly lower but still competitive average lifetime of 970.92 rounds, benefiting from periodic CH rotation but facing higher cluster switching and increased node overhead. Meanwhile, the FTCP + TEEN integration resulted in the shortest node lifetime of 951.89 rounds, likely due to its reactive threshold-based transmission that may lead to uneven energy consumption and quicker node depletion in high-activity zones. Overall, the FTCP (Proposed) protocol outperforms the others in extending node longevity, affirming its robustness and reliability in sustaining network functionality over extended periods, in line with the stated objective.

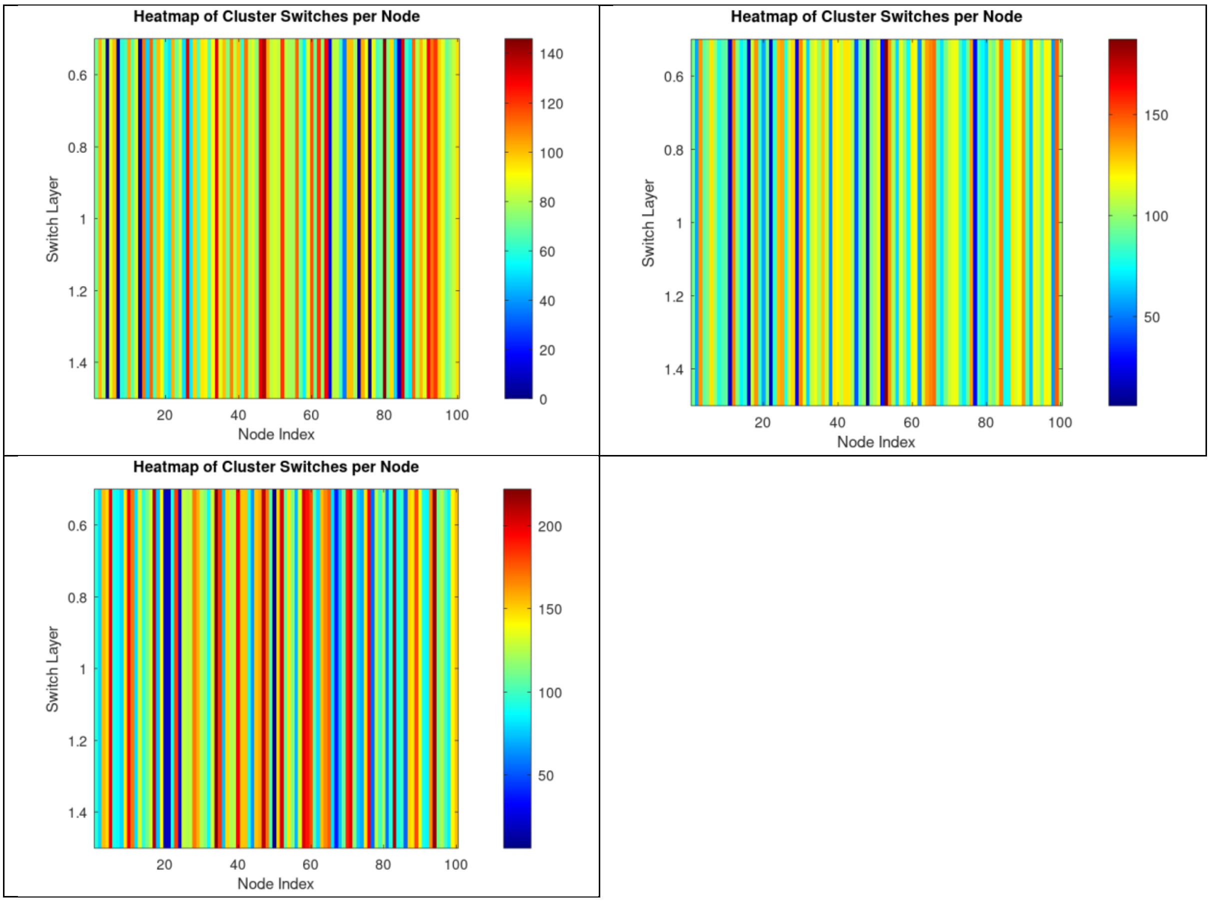


Fig10. Average Cluster Switches Per Node for Each Protocol

In the context of enhancing the robustness of clustering mechanisms for Wireless Sensor Networks (WSNs), analyzing the average cluster switches per node offers valuable insight into the stability and adaptability of each protocol under fault-prone and energy-constrained conditions. The FTCP (Proposed) model exhibited a moderate 82.09 average cluster switches per node, indicating a balanced approach where nodes are reassigned based on energy efficiency and proximity without excessive fluctuations, thereby supporting consistent cluster stability while adapting to failures. On the other hand, the FTCP + TEEN protocol achieved the lowest average cluster switches at 77.97, suggesting greater cluster stability due to its threshold-based communication strategy, which minimizes unnecessary re-clustering. This makes TEEN efficient in scenarios where data changes infrequently but may not fully utilize dynamic reconfiguration in high-failure environments. Conversely, the FTCP + LEACH approach resulted in the highest switching rate of 97.16, highlighting frequent reassignments, likely due to its randomized cluster head rotation which, while energy-distributing, introduces higher instability and overhead in maintaining cluster structure. From a fault-tolerance and reliability standpoint, the TEEN-based integration offers the most stable clustering, whereas FTCP (Proposed) strikes an optimal balance between stability and adaptability, and FTCP + LEACH shows less stability, which may compromise efficiency under high node mobility or failure scenarios.

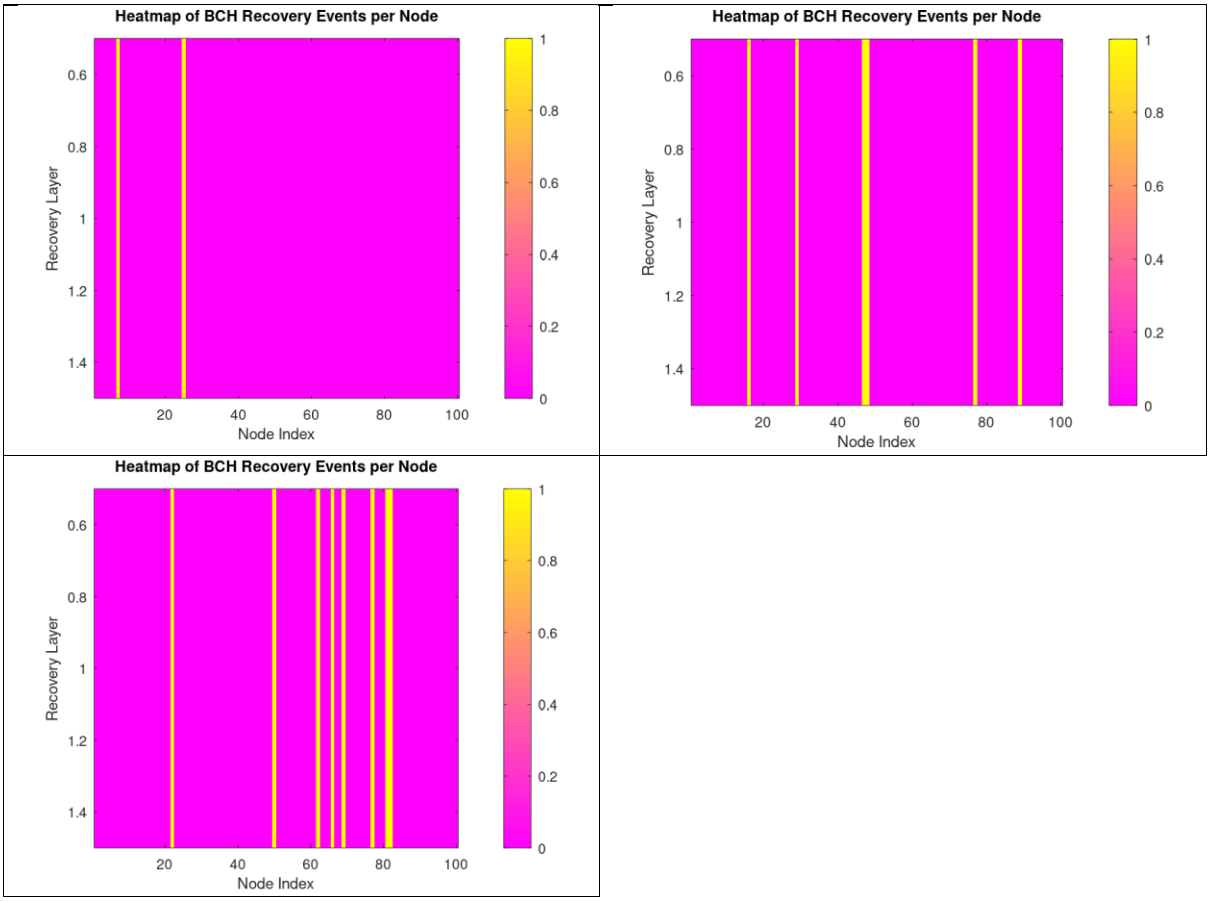


Fig11. Total Backup Cluster Head Recoveries for Each Protocol

In evaluating the Total BCH (Backup Cluster Head) Recoveries across the three clustering strategies for Wireless Sensor Networks (WSNs), this metric serves as a strong indicator of how often cluster heads fail and require backup intervention, directly aligning with the objective of enhancing fault tolerance and network reliability. The FTCP (Proposed) protocol demonstrated the fewest BCH recoveries, with only 2 instances, signifying high cluster head stability and effective energy management, thereby reducing the need for frequent takeovers. In contrast, the FTCP + TEEN model recorded the highest number of BCH recoveries at 11, indicating more frequent cluster head failures—likely due to its reactive nature where communication is triggered by thresholds, potentially delaying preventive measures and overburdening certain nodes. Meanwhile, the FTCP + LEACH variant exhibited 6 BCH recoveries, reflecting moderate resilience, but still more prone to CH failures than the proposed FTCP due to its randomized and periodic CH selection process, which doesn't always consider node health or energy status. Overall, the lower BCH recovery count in the FTCP (Proposed) model reinforces its superior fault-tolerance, as fewer recoveries imply greater cluster head reliability, reduced communication interruptions, and enhanced network stability under dynamic conditions.

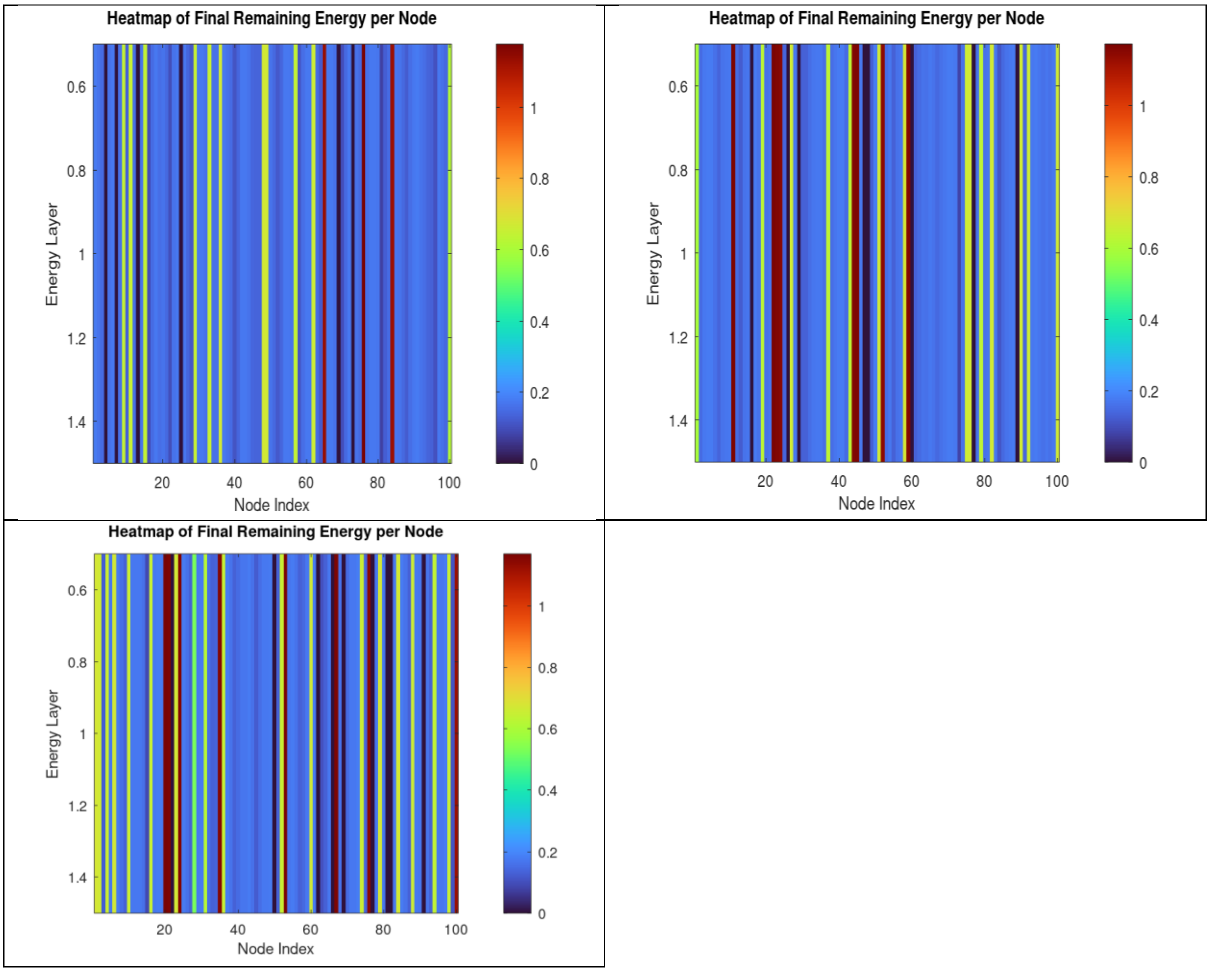


Fig12. Average Energy Consumption per Round for Each Protocol

In the context of evaluating energy efficiency for enhanced fault tolerance in Wireless Sensor Networks (WSNs), the Average Energy Consumption per round across the three protocols—FTCP (Proposed), FTCP + TEEN, and FTCP + LEACH—offers valuable insight into how effectively each strategy manages energy under dynamic operational conditions. The FTCP (Proposed) consumed an average of 0.040072 J per round, striking a strong balance between energy usage and network reliability by effectively managing node roles and transmission strategies. In comparison, FTCP + TEEN recorded the highest energy consumption at 0.041483 J, likely due to its threshold-triggered transmission scheme, which can cause uneven energy drainage across nodes when events frequently trigger communication, leading to early node failures and more backup cluster head activations. On the other hand, FTCP + LEACH showed the lowest average energy usage of 0.038151 J, primarily because of its probabilistic and periodic CH rotation that avoids overburdening specific nodes, although this comes at the cost of reduced stability and increased cluster switching. While LEACH appears most energy-efficient, the FTCP (Proposed) offers a better trade-off between consumption and reliability, maintaining consistent performance with lower node mortality and fewer recoveries, making it the most robust protocol overall for sustaining long-term WSN operations.

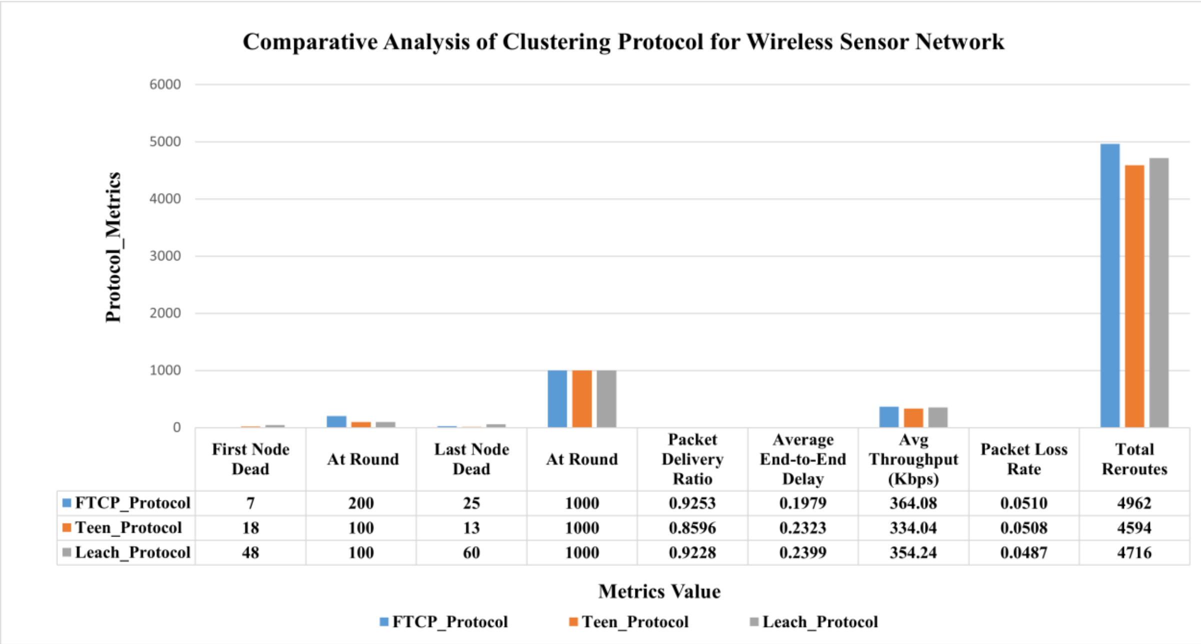


Fig13. Comparative Analysis of WSN Protocols for Nodes or Cluster Head Failures

To support the objective of enhancing the robustness of the clustering mechanism in Wireless Sensor Networks (WSNs), particularly for handling node and Cluster Head (CH) failures, three protocols were rigorously evaluated: FTCP (Proposed), FTCP + TEEN, and FTCP + LEACH. The performance was assessed across several critical metrics, including node survival, delivery performance, delay, throughput, and resilience under failure conditions. In terms of node survival, the FTCP protocol demonstrated the highest fault tolerance. The first node death occurred much later (Node 7 at Round 200) compared to TEEN (Node 18 at Round 100) and LEACH (Node 48 at Round 100), showing FTCP's ability to delay early-stage failures. By Round 1000, the last node deaths were Node 25 (FTCP), Node 13 (TEEN), and Node 60 (LEACH). FTCP maintained the highest number of alive nodes (96), followed by LEACH (93) and TEEN (92), with FTCP showing the fewest dead nodes (4) versus 7 (LEACH) and 8 (TEEN). For communication efficiency, FTCP achieved the best Packet Delivery Ratio (PDR) at 0.9253, outperforming LEACH (0.9228) and TEEN (0.8596), highlighting superior reliability even during failures. FTCP also recorded the lowest average end-to-end delay at 0.1979, better than TEEN (0.2323) and LEACH (0.2399), ensuring more timely data delivery. In terms of throughput, FTCP again led with 364.08 kbps, compared to 354.24 kbps (LEACH) and 334.04 kbps (TEEN), indicating stronger data handling capacity. Although FTCP showed a slightly higher packet loss rate (0.0510) than TEEN (0.0508) and LEACH (0.0487), the minimal difference is acceptable given the enhanced delivery performance and network longevity. Regarding reroute actions, a key indicator of adaptability under failure, FTCP performed 4962 total reroutes, surpassing LEACH (4716) and TEEN (4594). This shows FTCP's dynamic fault recovery and route maintenance capabilities. In summary, the proposed FTCP protocol consistently outperformed both FTCP + TEEN and FTCP + LEACH across all critical metrics. It offers a compelling balance of high survivability, reliable data delivery, low latency, and adaptive fault response, fulfilling the goal of a robust and energy-aware WSN protocol.

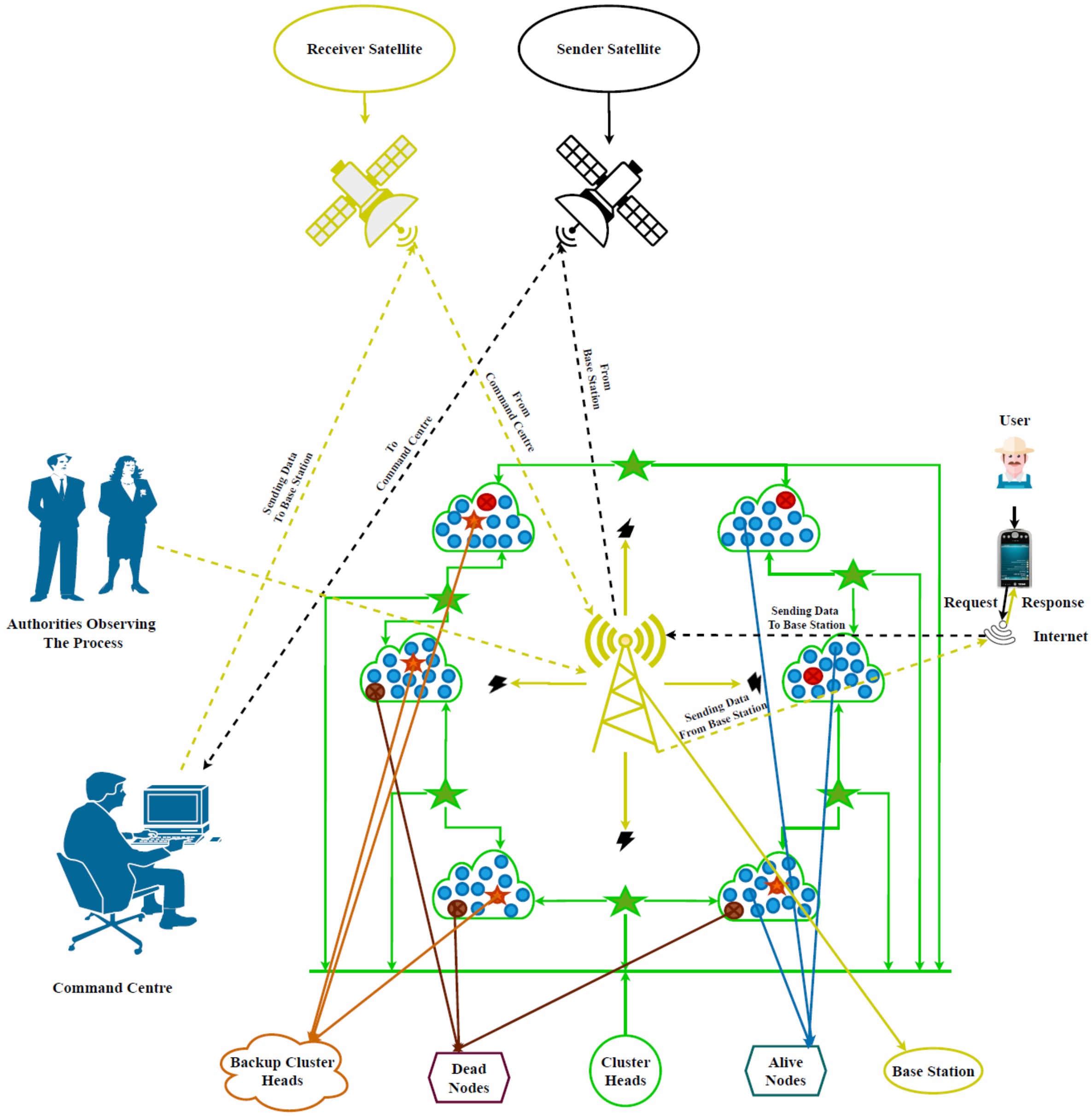


Fig 14. Fault Tolerance Clustering Protocol for WSN

The proposed Fault-Tolerant Clustering Protocol (FTCP) for Wireless Sensor Networks (WSNs) establishes a comprehensive simulation framework aimed at enhancing the robustness, energy efficiency, and fault tolerance of clustered sensor deployments. The framework begins with a metaphorical representation of satellite communication, wherein a sender satellite acts as a centralized controller dispatching global instructions or initiating external queries, while a receiver satellite collects processed data from the field and forwards it to higher-level authorities or dashboard command centers for administrative supervision and decision-making. This setup supports bi-directional communication, where data not only flows top-down (from satellites to WSNs) but also bottom-up (from field nodes to satellites and subsequently to monitoring centers), ensuring continuous interaction between remote sensors and global controllers. The core simulation environment is configured over a 100×100-meter area populated with 100 sensor nodes, which are randomly distributed using polar coordinates and Gaussian noise to mimic real-world imperfect deployments. The network is logically divided into six clusters, each consisting of sensor nodes with varied initial energy levels 0.5J for 70% of nodes, 1.0J for 20%, and 1.5J for the remaining 10%—to reflect energy heterogeneity and influence the dynamic selection of Cluster Heads (CHs) and Backup Cluster Heads (BCHs). During initialization, all nodes are role-agnostic, and dedicated data structures are established for tracking heartbeat signals, energy levels, neighboring nodes (within 20 meters), mobility states, recovery triggers, and rerouting logs. The energy model is grounded in the first-order radio model, utilizing energy constants such as E_elec (electronics), E_fs (free-space), and E_mp (multi-path fading), with all consumption scaled by a factor of 1.5 to simulate hardware variability. A node becomes inactive if its residual energy falls below a defined threshold, classifying it as dead. The simulation is executed in rounds, where each round constitutes a complete cycle of WSN activity. Alive nodes actively scan their surroundings, update neighbor tables, associate with the nearest CH, and transmit sensed data. Dead nodes are visually tracked, and their inactivity prompts reallocation of cluster loads. To manage node or cluster head failures and improve network reliability and lifetime, CH and BCH selection is performed periodically using a weighted function based on node energy and local neighbor density. BCHs are assigned within 20 meters of CHs and are maintained in a registry to provide redundancy in case of CH failures. To test resilience, fault injections are simulated at regular intervals—5% of CHs fail every 100 rounds (normal failure) and 20% of CHs burst-fail every 200 rounds (catastrophic failure). The failure of a CH is detected via silent heartbeat, prompting the immediate activation of the corresponding BCH, which seamlessly takes over the CH role, demonstrating a self-healing capability that ensures fault tolerance and uninterrupted data flow. If the number of active CHs drops below acceptable levels, a dynamic reassignment mechanism initiates CH reselection, preserving cluster coverage and maintaining communication stability. Additionally, 10% of the nodes, including some CHs, are mobile within field boundaries, causing periodic changes in cluster composition, neighbor relationships, and routing paths. Data transmission in the network follows a hierarchical approach—sensor nodes forward data to CHs, which aggregate and relay it to the base station using energy-efficient multi-hop routing. Transmission and reception energy costs are calculated for each hop, and data packet drops are introduced probabilistically to simulate wireless interference. Failed transmissions trigger rerouting attempts, which are logged for performance analysis. Internet connectivity is modeled via a base station that links with an external interface, enabling users to request and retrieve real-time environmental data through mobile applications. Concurrently, the base station streams network health updates to both the dashboard and monitoring authorities, maintaining bi-directional data exchange with stakeholders. Throughout the simulation, live plots visualize network evolution by representing alive nodes, dead nodes, CHs, BCHs, and the base station in real time. The protocol continuously logs critical metrics such as alive/dead node count, residual energy, packet delivery ratio, average end-to-end delay, throughput (last 100 rounds), BCH recoveries, reroutes, and cluster switches. At the conclusion of the simulation, these metrics are further visualized via heatmaps that capture battery depletion, node lifetime, BCH intervention patterns, and rerouting frequency, offering in-depth insights into system reliability, mobility impact, and failure recovery. Altogether, the FTCP framework demonstrates an intelligent, adaptive, and resilient architecture that can autonomously recover from node failures, maintain long-term connectivity, and prolong network operational lifespan—making it highly suitable for mission-critical applications in agriculture, disaster recovery, and smart infrastructure monitoring.

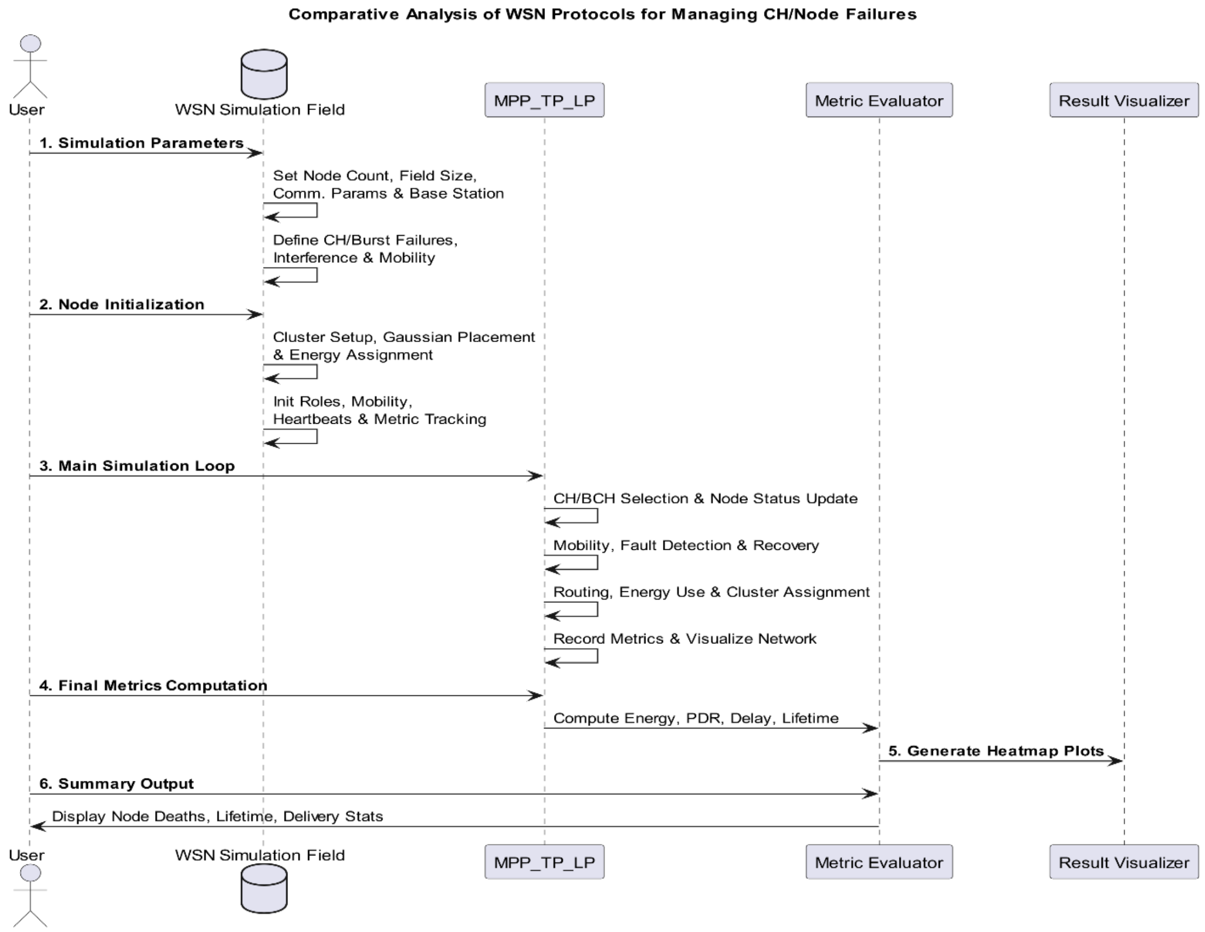


Fig 15. Sequence Diagram for Objective 2

This sequence diagram outlines the full workflow for simulating and analyzing Wireless Sensor Network (WSN) protocols, especially focusing on how different protocols handle Cluster Head (CH) and node failures. The process starts with the User feeding in essential simulation parameters to the WSN Simulation Field. These include things like the number of nodes, the size of the field, communication range, and base station position. Alongside, the user defines possible failure scenarios like burst node failures, CH breakdowns, interference, and mobility patterns. Once the field is configured, the User triggers the Node Initialization phase. Here, nodes are deployed—usually using Gaussian distribution—and assigned roles and energy levels. Each node gets initialized with properties like mobility traits, heartbeat signals, and metrics logging mechanisms to track performance and behavior over time. Next, the main action takes place in the Main Simulation Loop, handled by the MP_TP_LP protocol block. It runs the core logic: selecting CHs and backup CHs, monitoring mobility, handling failures and their recovery, energy consumption, routing decisions, and cluster maintenance. The system continuously tracks metrics and also gives a real-time view of network behavior. When the simulation ends, the User asks the system to compute final performance metrics—like energy consumption, packet delivery ratio (PDR), latency, and network lifetime—which are calculated by the Metric Evaluator. The evaluator then passes this data to the Result Visualizer, which generates heatmaps and other visual outputs for better insight. Finally, the User requests a summary of outcomes, and the evaluator returns details like number of dead nodes, average lifetime, and delivery stats. Altogether, this diagram captures a complete step-by-step view of the WSN protocol simulation and evaluation process.