Forest Fire Detection and Reporting

in Forests of Uttarakhand

A Wireless Sensor Network Approach for Early Detection and Reporting

October 26, 2025

Introduction: Forest Fire Threats and WSN Applications

Forest Fire Threats

- Common disaster globally, especially in winter months
- Over 100,000 forest fire incidents reported in the past decade
- Devastating impact on ecosystems and biodiversity
- Threat to human lives and property in fire-prone areas
- Significant economic losses to affected regions

WSN Applications

- Effective detection of forest fires through wireless sensor networks
- Unique advantages for deployment in complex forest terrains
- Real-time monitoring and early warning capabilities
- Efficient data reporting to multiple sink nodes
- Energy-efficient solutions for long-term deployment

Limitations of Existing Forest Fire Detection Systems

2D Node Deployment Assumptions

- Most existing solutions assume sensors deployed on a 2D plane
- Forest deployment in rugged areas with mountains, rocks, and dense underbrush
- Airdropping is only feasible deployment method
- Nodes deploy at different heights (ground, treetops, underbrush)
- Each node has different Z coordinate - requires 3D deployment

Single-Sink Node Design

- Almost all existing solutions report data to a single sink node
- Creates a single point of failure risk
- Network fire reporting function fails if sink node dies
- Unacceptable for critical applications like fire early warning
- Redundant design needed for reliable operation

Additional limitation: Some research assumes grid deployment, which is unrealistic for dense forests and overestimates network lifetime.

Challenges in Real Forest Environments

Complex Terrain

Forest fire detection systems deployed in rugged areas with mountains, rocks, and dense vegetation

Variable Heights

Nodes distributed at different heights (ground, tree tops, underbrush) with varying Z coordinates

Deployment Method

Aerial deployment is often the only feasible method in remote forest areas

Wildlife Interference

Grid deployment impractical due to complex terrain and wildlife concerns

Why Random 3D Deployment is More Realistic

Actual Deployment

Random deployment better represents the actual distribution of nodes in complex forest environments

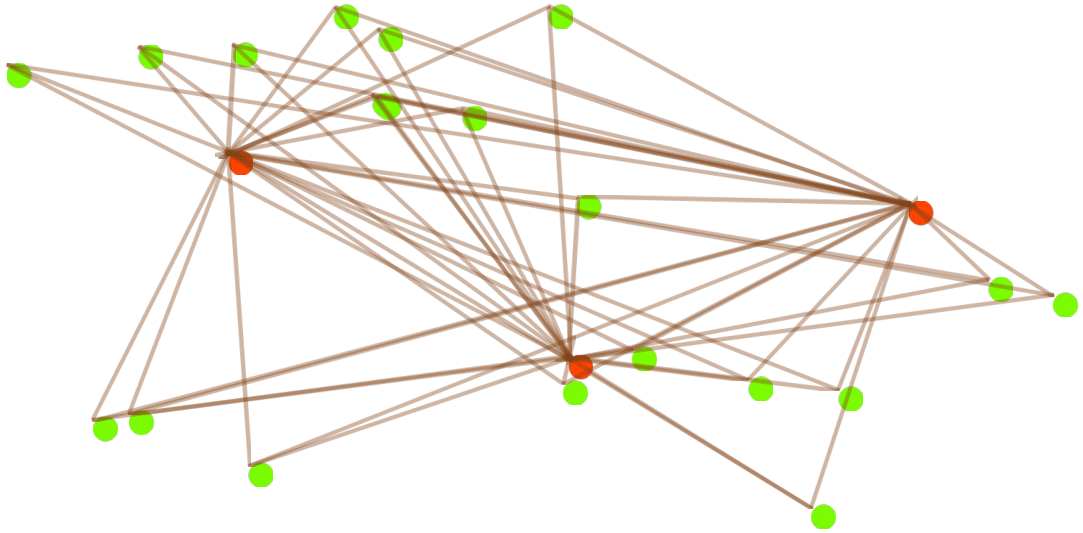
Network Lifetime

Grid deployment overestimates network lifetime, potentially leading to missed fire detections

Random 3D Deployment in Forest Environment

Proposed 3D Multi-Sink WSN Solution

3D Random Node Deployment



Nodes deployed in 3D space to match complex forest terrain

Multi-Sink Design

Sink Node 1 **Sink Node 2** **Sink Node 3**

Data reported to multiple sinks for reliability

Key Features

3D Random Deployment

Nodes deployed in 3D space to match complex forest terrain (ground, tree tops, shrubs)

Multi-Sink Redundancy

Data reported to three different sink nodes, reducing single point failure probability

Energy Efficiency

Protocol designed to improve network lifetime while ensuring no fire detection is missed

Network Lifetime

Defined as time until first node exhausts energy (n-out-of-n model)

System Model and Radio Model

System Model

- **3D Random Deployment:** n nodes randomly deployed in a 3D Cartesian plane
- **Multi-Sink Architecture:** nodes report to three different sink nodes
- **Redundancy:** design reduces probability of single point failure

Key Parameters:

- Network lifetime: time from deployment to first node depletion
- Path loss index: typically 3 in forest environments

Radio Model

- **Energy Components:** sensing, computation, forwarding, receiving, listening

Energy Consumption Formulas

$$E_{TX} = m * 117 * 10 + m * 1.7 * 10 + D * m * \varepsilon * d$$

$$E_{listening} = (1 - D) * 570 * 10$$

Where: m = packet size (bits), D = duty cycle, ε = 8.854 pJ/bit/m², d = distance between nodes

- **Computational Energy:** 117 nJ/bit
- **Sensing Energy:** 1.7 µJ/bit

Fermat Point-Based Energy Efficient Data Forwarding

Fermat Point Concept

The Fermat point within a quadrilateral is the point that minimizes the sum of distances to all vertices.

Forwarding Mechanism Flow

1. **Fermat Point Calculation:** Nodes calculate the theoretical Fermat point using the Minima algorithm.
2. **Fermat Node Selection:** The closest node to the Fermat point is selected as the Fermat Node (FN).
3. **Data Transmission to FN:** Source nodes transmit data to their respective Fermat nodes.
4. **FN Forwarding to Sinks:** Fermat nodes transmit data to all three sink nodes.

Next Hop Selection Formula

$$K_{ij} = \frac{res\_energy_i}{dist_j}$$

Where: res_energy_i = Remaining battery charge of node i (mJ), $dist_j$ = Distance from node j to sink

Data Transmission via Fermat Node

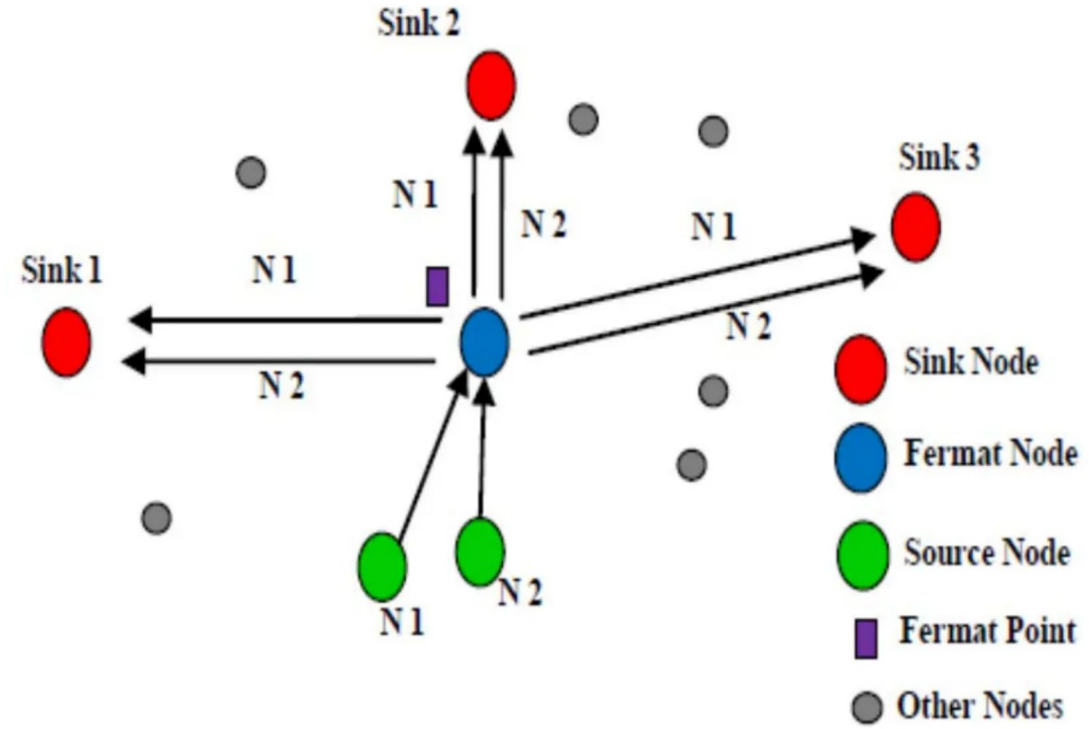


FIGURE 2
NODES TRANSMITTING DATA THROUGH FERMAT NODE TO THREE DIFFERENT SINKS.

Key Benefits

Data Transmission Modes

Time-driven Mode

- All nodes periodically sense temperature, humidity and solar radiation
- Data sent to all three sink nodes through FN
- Uses TDMA with fixed time slots for transmission

Characteristics:

Highest redundancy, highest energy consumption, shortest network lifetime

Event-driven Mode

- Nodes respond only when temperature exceeds 50°C threshold
- Sends wind direction to estimate fire spread
- Random node selection for probing

Characteristics:

Reduced redundancy, lower energy consumption, longer lifetime than time-driven mode

Hybrid Mode

- Combines time-driven and event-driven approaches
- Nodes transmit in polling mode during fixed time slots
- Only transmits when temperature exceeds threshold

Characteristics:

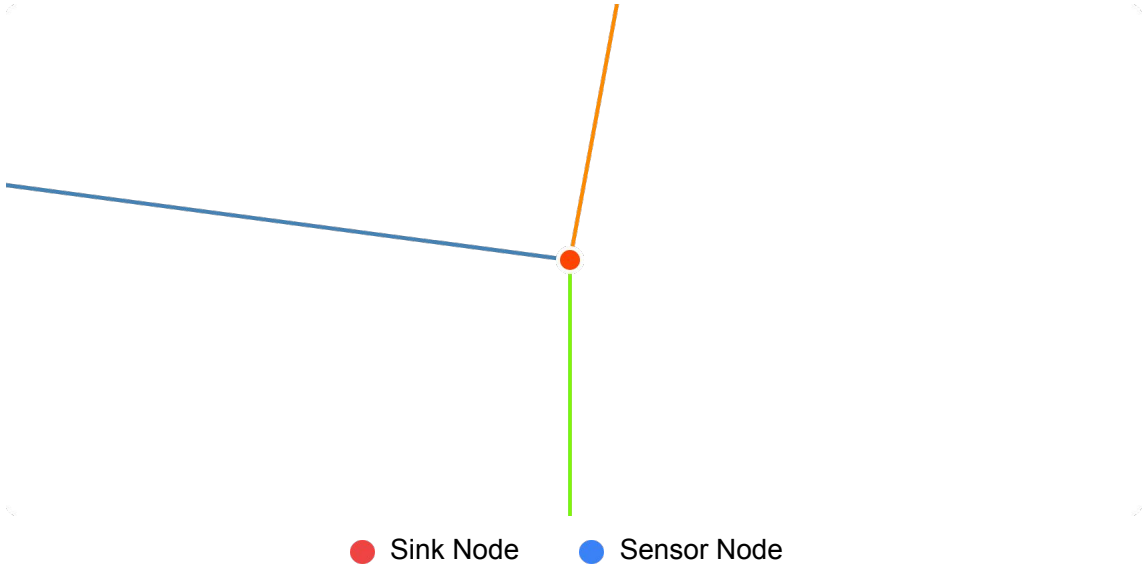
Best of both worlds, expected to have the longest network lifetime

Feature	Time-driven	Event-driven	Hybrid
Power Consumption	High	Medium	Low
Network Lifetime	Short	Medium	Long
Redundancy	High	Medium	Low

Simulation Environment and Parameters

3D Simulation Environment

Simulation area: 100m × 100m × 100m three-dimensional Cartesian plane



Sink Node Positions

- Sink 1: <0, 0, 0>
- Sink 2: <100, 0, 0>
- Sink 3: <100, 100, 100>

Network Parameters

TABLE 1
NETWORK PARAMETERS

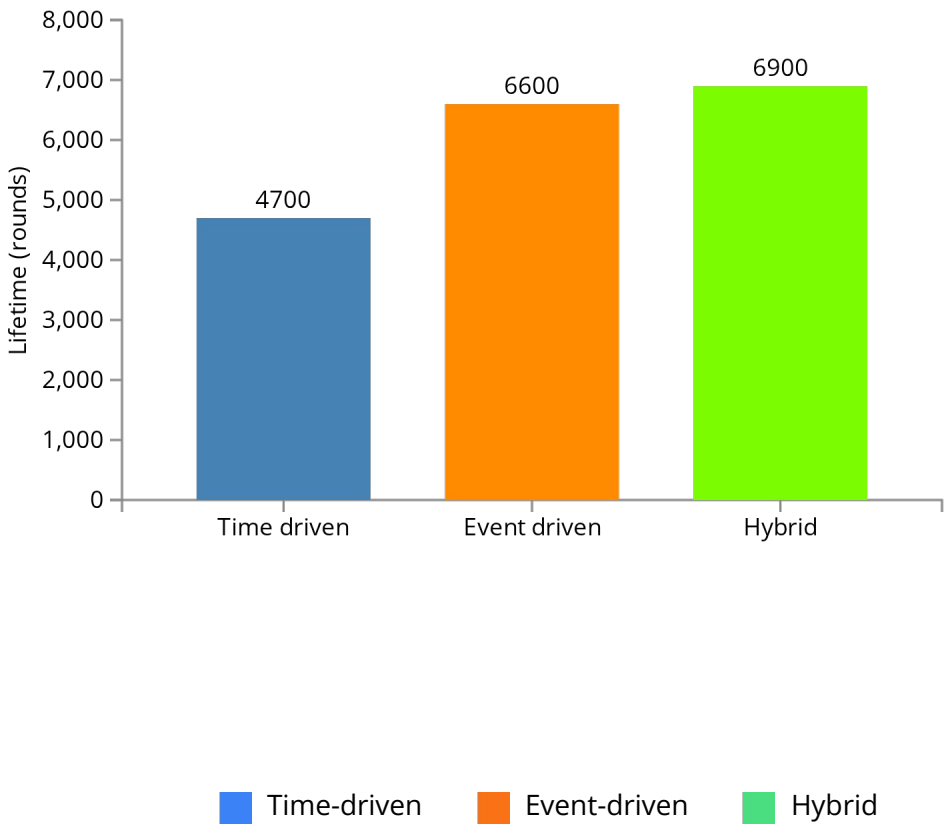
Parameter	Value
Number of nodes	200
Number of sinks	3
Path Loss Exponent	3
Initial Energy of Nodes	1 J
Deployment Pattern	RANDOM

Parameter Descriptions

- **Number of nodes:** 200 sensor nodes deployed in the environment
- **Number of sinks:** 3 aggregation nodes for data reporting
- **Path Loss Exponent:** 3, affecting signal propagation
- **Initial Energy:** 1 Joule for each sensor node
- **Deployment Pattern:** Random distribution in 3D space

Network Lifetime Comparison

Lifetime Comparison between Different Transmission Modes



Key Insights

- Network lifetime defined as n-out-of-n (time from deployment to first node energy depletion)
- Hybrid mode provides the highest network lifetime (6900 rounds)
- Time-driven mode has shortest lifetime (4700 rounds) due to unnecessary transmissions
- Event-driven mode performs better than time-driven (6600 rounds) by transmitting only when necessary

Why Hybrid Mode Performs Best

Hybrid mode combines the advantages of both time-driven and event-driven approaches, achieving optimal energy efficiency through scheduled polling while only transmitting when necessary events occur.

Conclusions and Future Work

Key Conclusions

- Hybrid transmission mode provided the longest network lifetime
- Time-driven mode suitable for wide forest environment research

Future Work

- Deploy real nodes in Mussoorie-Dehradun region
- Measure effectiveness of the proposed solution

Thank You for Your Attention

Questions?