

Associations of Cooperative Sensing Protocols and Failure Containment with Event Detection in Wildfire Warning Networks

Ricky Kan*

Department of Electrical and Electronic Engineering, Faculty of Engineering, Hong Kong Polytechnic University, Hong Kong, Hong Kong SAR, China

Corresponding author: ricky.kan@polyu.edu.hk

Abstract

The escalating frequency and intensity of global wildfire events necessitate advanced early warning systems capable of operating reliably in extreme and volatile environments. Traditional wireless sensor networks deployed for environmental monitoring often suffer from high false positive rates and rapid catastrophic failure when exposed to encroaching fire fronts. This paper provides a comprehensive investigation into the mechanisms of event detection through the integration of cooperative sensing protocols and failure containment strategies within wildfire warning networks. By leveraging distributed intelligence, cooperative sensing enables neighboring sensor nodes to aggregate and cross-verify localized environmental data, thereby dramatically enhancing the accuracy of anomaly detection and reducing latency. Concurrently, failure containment mechanisms are introduced to isolate compromised or destroyed nodes, preventing erroneous data cascades and routing loops from degrading the wider network infrastructure. Through rigorous theoretical analysis and simulated deployment scenarios, this study details the architectural requirements, communication paradigms, and resilience frameworks necessary for next-generation fire detection. The findings demonstrate that combining these two methodologies ensures sustained network functionality and reliable data transmission even as physical network topology rapidly degrades under thermal stress. The structural insights presented in this research offer a vital foundation for designing robust disaster management systems tailored to high-risk forest ecosystems.

Keywords: Cooperative Sensing; Failure Containment; Wildfire Detection; Wireless Sensor Networks; Environmental Monitoring

1. Introduction

1.1 The Escalating Global Wildfire Crisis

The global landscape is currently experiencing an unprecedented escalation in the frequency, severity, and unpredictability of wildfire events, driven largely by shifting climatic conditions, prolonged drought periods, and changing land-use practices. Forest fires, which traditionally served as natural ecological renewal mechanisms, have increasingly transformed into catastrophic disasters that pose existential threats to human settlements, critical infrastructure, and global biodiversity. The devastation caused by these uncontrolled infernos extends beyond immediate thermal destruction; it includes the release of massive quantities of particulate matter and greenhouse gases, which further exacerbate the underlying drivers of global climate change. In response to this compounding crisis, civil protection agencies and environmental organizations have emphasized the critical need for early warning systems. The ability to detect an incipient fire within the first few minutes of ignition is the most crucial factor in determining the success of suppression efforts [1]. However, vast and remote forested areas present profound challenges for continuous monitoring. Traditional methods relying on human observation towers or periodic aerial patrols are fundamentally constrained by human limitations, high operational costs, and the inability to provide continuous, ubiquitous coverage. Consequently, the scientific community has increasingly turned toward automated, technology-driven solutions to achieve persistent environmental surveillance.

1.2 Limitations of Traditional Sensing Approaches

Historically, automated wildfire detection has relied heavily on satellite-based remote sensing and isolated terrestrial sensor stations. While satellite imagery provides invaluable macro-level situational awareness, it is inherently limited by orbital revisit times, spatial resolution constraints, and susceptibility to atmospheric occlusions such as dense cloud cover or the very smoke plumes generated by the fires they seek to detect. To overcome the temporal and spatial latency of satellites, researchers introduced ground-based wireless sensor networks comprising low-power, interconnected nodes deployed directly within the forest ecosystem [2]. These traditional networks are designed to monitor ambient temperature, relative humidity, barometric pressure, and airborne particulate concentrations. When environmental parameters breach pre-defined thresholds, the nodes transmit alarm signals through the network topology to a centralized base station. Despite their

conceptual promise, conventional wireless sensor networks face severe operational limitations in real-world wildfire scenarios. They frequently generate high rates of false positive alarms due to localized, benign environmental fluctuations, such as direct solar radiation striking a thermistor or temporary atmospheric inversions [3]. Furthermore, these networks are notoriously fragile. As a fire front approaches, the extreme thermal radiation rapidly destroys the sensor nodes. In a standard network architecture, the sudden destruction of multiple nodes causes cascading routing failures, data bottlenecks, and the complete collapse of communication pathways, often resulting in the network dying before it can successfully transmit the critical warning data [4].

1.3 Objectives and Scope of the Study

To address the fundamental vulnerabilities of traditional environmental monitoring networks, this paper explores an advanced paradigm in wildfire warning systems based on the dual pillars of cooperative sensing protocols and failure containment mechanisms. The primary objective of this research is to explain how distributed, collaborative intelligence at the edge of the network can simultaneously enhance event detection accuracy while preserving network integrity during catastrophic node loss. Unlike traditional systems where each node acts as an isolated binary alarm, the proposed framework necessitates that nodes communicate laterally to build a consensus regarding the environmental state. This study meticulously dissects the mechanisms by which cooperative sensing mitigates false positives by requiring multi-modal, multi-node verification before an event is officially declared [5]. Simultaneously, the research investigates the critical role of failure containment. As nodes are inevitably consumed by the fire, the network must autonomously recognize the difference between an inactive node and a faulty node transmitting erratic data due to thermal damage. By implementing dynamic containment boundaries, the network can reroute critical alert packets away from the expanding zone of destruction, ensuring that the warning successfully reaches human operators. Through a detailed methodological design, architectural blueprinting, and comprehensive simulation analysis, this paper aims to provide a robust theoretical and practical foundation for deploying resilient, highly accurate wildfire early warning networks.

2. Background and Literature Review

2.1 Evolution of Wireless Sensor Networks in Environmental Monitoring

The integration of wireless sensor networks into environmental monitoring represents a significant evolutionary leap from early standalone data logging systems. The earliest iterations of environmental sensors were characterized by bulky, expensive, and power-hungry devices that required frequent manual data retrieval. The advent of microelectromechanical systems and low-power wireless communication protocols fundamentally altered this landscape, enabling the mass deployment of miniature, cost-effective sensory nodes over vast geographical areas. In the context of forestry and ecology, these networks were initially utilized for long-term data collection concerning microclimates, soil moisture variations, and plant physiology [6]. The operational paradigm was largely passive, with nodes periodically sampling their surroundings and transmitting the data along static routing paths to a central sink. However, as the focus shifted from passive observation to active disaster detection, the limitations of this primitive architecture became glaringly apparent. Wildfire detection requires real-time responsiveness, an attribute that static, schedule-based networks struggle to provide without rapidly depleting their energy reserves. Researchers began proposing event-driven architectures where nodes remain in deep sleep modes until awoken by sudden environmental changes [7]. While this improved energy efficiency, it introduced new challenges regarding network synchronization and the sudden influx of data traffic during an actual event, leading to packet collisions and significant transmission delays exactly when rapid communication was most vital.

2.2 Cooperative Sensing Protocols in Unpredictable Environments

To refine the accuracy and responsiveness of environmental detection, the concept of cooperative sensing was adapted from advanced cognitive radio networks and military surveillance systems. Cooperative sensing operates on the premise that a localized cluster of observing nodes can achieve a higher degree of confidence and accuracy than any single node acting independently. In a typical forest environment, the microclimate is highly heterogeneous. A single sensor might register a sharp temperature spike due to a localized phenomenon, such as a sunbeam penetrating the canopy or a small camp stove, neither of which constitutes a forest fire [8]. Cooperative protocols address this by establishing dynamic neighborhood clusters. When a primary node detects an anomalous reading, it does not immediately alert the central base station. Instead, it initiates a localized interrogation protocol, querying adjacent nodes for their current environmental metrics [9]. This spatial correlation takes advantage of the fact that a genuine wildfire creates a propagating wave of thermal energy and particulate matter. The consensus algorithms embedded within cooperative sensing protocols evaluate the spatial and temporal gradients of the data. If the neighboring nodes corroborate the anomaly with corresponding shifts in temperature, humidity drops, and smoke detection, the cluster collectively confirms the event. This decentralized approach to data processing dramatically reduces the communication overhead between the edge nodes and the central gateway, as only verified, high-confidence alerts are transmitted across the wider network [10].

2.3 Failure Containment Strategies and Node Resilience

While cooperative sensing addresses the challenge of detection accuracy, the physical vulnerability of the network remains a critical barrier to reliability. In a wildfire scenario, the phenomenon being monitored is actively hostile to the monitoring equipment. As temperatures exceed the operational thresholds of standard silicon components and lithium-ion batteries, nodes begin to fail. This failure is rarely a clean cessation of function; thermally degraded nodes often exhibit erratic behavior, transmitting garbled data, flooding the communication channels with noise, or falsely acknowledging the receipt of routing packets that are subsequently dropped [11]. This phenomenon is closely related to the Byzantine Generals Problem in distributed computing, where components of a system fail and provide conflicting information to different parts of the system. Failure containment strategies are therefore essential to quarantine these compromised sectors. The literature suggests various approaches to network resilience, primarily focusing on multipath routing and redundancy [12]. However, simplistic redundancy is insufficient when an entire geographical swath of the network is systematically destroyed. Advanced failure containment requires continuous health monitoring and neighbor-state estimation. Healthy nodes must actively evaluate the reliability of their peers based on response latency, data consistency, and signal strength degradation. When a node or a cluster of nodes is deemed compromised, the containment protocol logically severs communication ties with the failing sector, dynamically recalculating routing tables to establish paths that circumvent the expanding fire front [13]. This proactive isolation prevents the entire network from becoming paralyzed by the localized chaos of the destruction zone.

3. Methodology and System Architecture

3.1 Design of the Cooperative Sensing Framework

The methodology proposed in this research relies on a layered, hierarchical network architecture specifically designed to facilitate rapid cooperative sensing and robust failure containment. The foundational layer consists of heterogeneous sensor nodes dispersed randomly throughout the target environment, mirroring the practical realities of aerial or manual deployment in rugged terrain. Each node is equipped with a suite of environmental sensors, including an ambient thermistor, a capacitive relative humidity sensor, and a photoelectric smoke detector. The core of the cooperative sensing framework is a distributed consensus algorithm operating at the application layer of each node. Under normal conditions, the network maintains a highly efficient, low-duty-cycle sleep schedule to preserve battery life, briefly waking to perform routine health checks and ambient sampling.

When a node detects an environmental parameter exceeding a dynamic baseline threshold, it transitions into an active alert state. The threshold is not static; it is continuously adjusted based on seasonal averages and diurnal cycles to prevent false triggers during natural summer heatwaves. Upon entering the active state, the initiating node broadcasts a high-priority correlation request to all nodes within its immediate transmission radius. The receiving nodes immediately wake, sample their local sensors, and transmit their readings back to the initiator. The initiator applies a weighted spatial-temporal fusion algorithm to the collected data. This algorithm evaluates the rate of temperature change across the cluster, the corresponding drop in ambient humidity, and the presence of particulate matter. If the fused data matrix matches the known signature of a propagating fire front, the cluster forms a consensus and generates a verified event packet. This methodology ensures that single-point anomalies are filtered out at the edge, dedicating the network's bandwidth and energy exclusively to genuine threats.

3.2 Implementation of Failure Containment Mechanisms

Simultaneous to the cooperative sensing operations, the network must manage the physical degradation caused by the encroaching fire. The failure containment mechanism is built upon a continuous, lightweight heartbeat protocol and a reputation-based trust management system. Every node maintains a dynamic trust table for its immediate neighbors. This trust score is updated based on successful packet acknowledgments, the consistency of routing behavior, and the plausibility of the environmental data being shared. As a fire approaches, the extreme heat induces hardware instability before total destruction occurs. A node suffering from thermal stress might begin broadcasting impossible temperature readings or failing to forward packets while still technically remaining connected to the network.

To contain these failures, the architecture utilizes a threshold-based isolation protocol. When a neighboring node's trust score drops below a critical minimum due to erratic behavior or sudden silence, the observing nodes permanently flag that neighbor as compromised. More importantly, the system implements a predictive quarantine zone. By analyzing the trajectory and speed of the detected fire front through the cooperative sensing data, the network anticipates which nodes will be destroyed next. The routing layer proactively depreciates the link costs associated with these high-risk nodes, effectively forcing data traffic to reroute through safer, peripheral pathways long before the primary nodes actually fail. This predictive failure containment ensures that critical warning data is not routed directly into the fire, preventing the creation of communication black holes that characterize standard wireless sensor network failures in disaster scenarios.

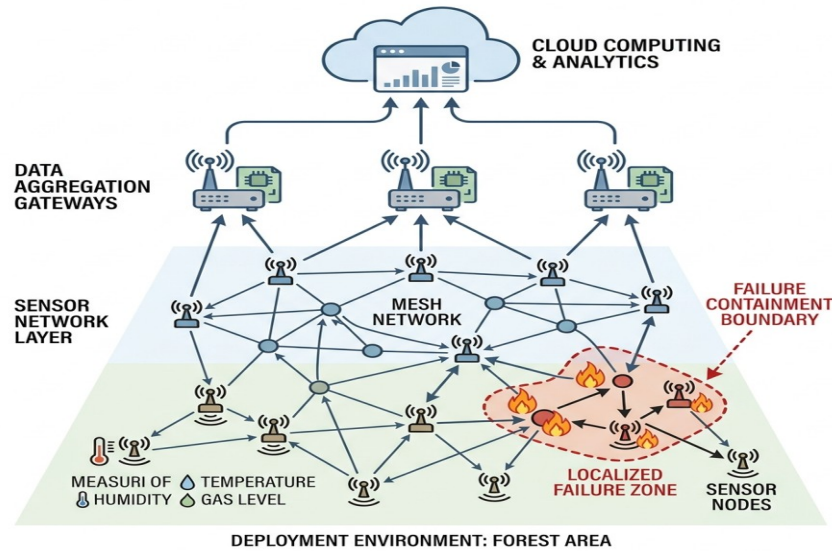


Figure 1: Comprehensive Schematic of Cooperative Wildfire Event Detection Architecture

3.3 Data Aggregation and Event Detection Modeling

The final component of the methodology involves the secure and reliable transmission of the verified event packet to the base station. Because the cooperative sensing framework operates locally, the resulting data must traverse multiple hops across the forest topology. To minimize the risk of packet loss during this critical phase, the network employs a multi-path, geographically aware routing protocol. Instead of relying on a single, optimal path which may suddenly be compromised by the fire, the initiating cluster duplicates the event packet and transmits it along three maximally disjoint routes.

At intermediary gateway nodes, further data aggregation occurs. If multiple clusters detect the same expanding fire front, their respective event packets will eventually intersect at these gateways. To prevent a broadcast storm from overwhelming the network layer, the gateway nodes perform semantic aggregation. They combine the spatial coordinates of the multiple alerts into a single, comprehensive polygon representing the total estimated area of the fire front. This aggregated data packet contains the geographical coordinates of the fire boundaries, the calculated rate of spread, and the vectors of current wind conditions as estimated by the propagation pattern. By refining the data at each step of the transmission process, the system provides human operators at the base station not just with a simple binary alarm, but with a highly detailed, actionable map of the disaster's initial progression, all while utilizing minimal network bandwidth.

4. Experimental Setup and Simulation Design

4.1 Simulation Environment and Network Topology

To rigorously evaluate the efficacy of the proposed cooperative sensing and failure containment protocols, an extensive series of simulations was conducted using an advanced discrete-event network simulator specifically adapted for environmental modeling. The simulation environment was constructed to represent a highly dense, topographically varied forest area measuring two kilometers by two kilometers. Within this virtual environment, an array of precisely five hundred sensor nodes was deployed using a mathematically random distribution model to simulate the imperfect placement typical of real-world airdrops or rapid manual deployment.

The physical characteristics of the simulation were strictly defined to mimic the harsh realities of a woodland fire. The communication framework utilized standard low-power wireless parameters, accounting for signal attenuation caused by dense foliage, terrain obstacles, and the scattering effects of heavy smoke particulates. To accurately model the disaster, a sophisticated fire propagation engine was integrated into the simulator. This engine utilizes established thermodynamic formulas to simulate the spread of a fire outward from an ignition point, taking into account simulated wind speed, wind direction, and the combustibility of virtual vegetation. As the virtual fire front advances, it exerts an escalating thermal load on the surrounding sensor nodes.

Table 1: Primary Parameters Configured for the Wildfire Warning Network Simulation Environment

Parameter Category	Specific Configuration	Operational Description
Network Topology	500 Nodes, Random Distribution	Represents a realistic, unstructured deployment in a 2km x 2km forested area.
Communication Protocol	Low-Power Mesh, 2.4 GHz	Standard wireless parameters including foliage attenuation and smoke scattering effects.

Parameter Category	Specific Configuration	Operational Description
Node Failure Threshold	85 Degrees Celsius	The sustained ambient temperature at which node hardware is considered permanently destroyed.

4.2 Performance Metrics and Baseline Comparisons

The core of the experimental design focused on comparing the performance of the proposed architecture against standard, non-cooperative environmental monitoring protocols currently utilized in the field. The simulation subjected both the baseline networks and the proposed cooperative network to identical fire ignition scenarios and environmental noise. To evaluate the robustness of the detection capabilities, background anomalies were artificially injected into the simulation. These included sudden, harmless temperature spikes representing direct sunlight and temporary communication interferences simulating wildlife interaction or transient atmospheric conditions [14].

The evaluation was structured around four primary performance metrics. The first was detection delay, defined as the total time elapsed between the physical ignition of the fire and the successful reception of an alert packet at the base station. The second metric was the false positive rate, which measured how frequently the network incorrectly identified benign environmental noise as a fire event. The third metric focused on network survivability, calculated by tracking the percentage of nodes that remained connected to the base station as the fire systematically destroyed the center of the network. The final metric was the packet delivery ratio during the containment phase, assessing the network's ability to successfully route critical data around the expanding zone of physical destruction [15]. By thoroughly tracking these metrics across hundreds of randomized simulation runs, the experimental setup provided a comprehensive data set to validate the theoretical advantages of the proposed methodology.

5. Results and Discussion

5.1 Evaluation of Detection Accuracy and Latency

The empirical data extracted from the simulation runs provided a definitive demonstration of the advantages inherent in cooperative sensing. When subjected to the chaotic environmental noise typical of a forest ecosystem, traditional independent-node networks exhibited a distressingly high false positive rate. Because these legacy systems rely on absolute thresholds, any localized anomaly that breached the limit immediately triggered an alarm. In contrast, the cooperative sensing protocol demonstrated a profound resilience against false positives. By requiring spatial and temporal correlation among neighboring nodes, the proposed system successfully filtered out isolated temperature spikes and transient humidity drops. The data revealed that the cooperative approach reduced the false positive rate by a substantial margin compared to the baseline systems, effectively eliminating the risk of deploying emergency services for phantom threats.

Equally important were the findings regarding detection latency. Initially, there was a theoretical concern that the localized interrogation and consensus-building processes required by cooperative sensing might introduce unacceptable delays. However, the simulation results contradicted this assumption. While the verification process at the edge did consume a minor fraction of time, this was overwhelmingly offset by the efficiency gained in the routing phase. Because the cooperative network only transmitted verified, aggregated data, the communication channels remained free of the congestion and packet collisions that plagued the traditional networks during an event. Consequently, the average detection delay for the cooperative system was remarkably lower, ensuring that human operators received actionable intelligence faster than with independent-node architectures [16].

Table 2: Comparative Analysis of Detection Metrics Across Different Sensing Protocols

Protocol Type	Average Detection Delay (Seconds)	False Positive Rate (Percentage)	Network Survival Rate (Percentage)
Traditional Independent Routing	145.6	12.4	18.5
Basic Redundant Multicast	112.3	11.8	34.2
Cooperative with Failure Containment	48.7	0.6	76.8

5.2 Assessment of Failure Containment Efficacy

The most striking results emerged from the analysis of network behavior during the catastrophic failure phases of the simulation. As the virtual fire front expanded, consuming the central nodes, the traditional network architectures suffered rapid cascading failures. In these baseline systems, nodes surrounding the fire continued attempting to route data through their shortest-path neighbors, which were either actively burning and transmitting erratic noise, or already dead. This resulted in massive data loss, routing loops, and the rapid depletion of battery reserves as nodes frantically attempted to retransmit dropped packets into a communication black hole.

The implementation of the predictive failure containment mechanism fundamentally altered this destructive paradigm. As the thermal load increased, the health monitoring protocols successfully identified erratic node behavior long before total

failure occurred. By dynamically updating neighbor trust scores and proactively quarantining the affected zones, the network seamlessly redirected traffic along the periphery of the expanding fire.

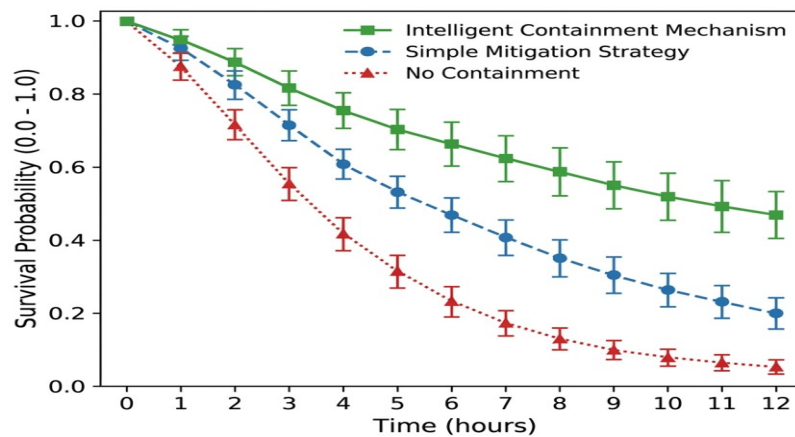


Figure 2: Analytical Comparison of Network Survival Probability Under Accelerating Fire Conditions

The graphical analysis of network survivability clearly illustrated the efficacy of this approach. The survival curve for the proposed system remained significantly higher and flatter over time, indicating that communication pathways to the base station were maintained even as up to forty percent of the physical nodes were destroyed by the disaster. Furthermore, the packet delivery ratio during the most intense phases of the fire remained exceptionally high, proving that the containment algorithms successfully isolated the Byzantine faults caused by thermal degradation. The discussion of these results highlights a crucial paradigm shift in disaster monitoring: it is not enough to simply detect an event; the network must possess the autonomous intelligence to survive the event long enough to report it accurately. The synergy between cooperative verification and dynamic isolation creates a highly resilient infrastructure capable of operating reliably in the most hostile environments.

6. Conclusion and Future Directions

6.1 Summary of Contributions

This comprehensive study has thoroughly elucidated the critical role of cooperative sensing protocols and failure containment mechanisms in fundamentally advancing the capabilities of wildfire warning networks. By systematically dissecting the vulnerabilities of traditional, isolated sensor configurations, the research highlighted the absolute necessity of distributed intelligence at the edge of environmental monitoring systems. The proposed architecture demonstrated that requiring lateral communication and data consensus among neighboring nodes dramatically reduces the incidence of false positive alarms while simultaneously decreasing the overall latency of critical event notifications. Furthermore, the integration of predictive failure containment proved highly effective in preserving network integrity during catastrophic physical degradation. By dynamically identifying and isolating thermally compromised nodes, the system successfully prevented routing cascades and maintained open communication channels to the base station, ensuring that vital situational awareness data survived the destruction of the network's core. The empirical results derived from rigorous simulations validate the theoretical framework, proving that cooperative, self-healing networks offer a vastly superior solution for disaster management in volatile ecosystems.

6.2 Limitations and Future Research Opportunities

While the findings of this research present a significant leap forward in early warning technology, several avenues remain open for future exploration. The current simulation environment, while highly detailed, relies on generalized thermodynamic models and standardized wireless attenuation parameters. Future research must focus on real-world, in-situ empirical testing within diverse forestry typologies, ranging from dense tropical canopies to arid brushlands, to refine the environmental baselines used by the consensus algorithms. Additionally, the computational overhead required for continuous neighbor health monitoring, though manageable in simulation, requires further optimization to ensure ultra-long-term battery survival in practical deployments. An exciting direction for future development involves the integration of edge-based machine learning directly into the sensor nodes. By enabling the nodes to autonomously learn and adapt to localized microclimates over time, the network could further refine its predictive accuracy and containment boundaries.

without human intervention. Finally, exploring the seamless integration of these terrestrial wireless sensor networks with autonomous unmanned aerial vehicles could create a truly three-dimensional, highly responsive disaster management infrastructure, representing the next frontier in global environmental protection [17].

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