Real-Time Wireless Mesh Networks for Disaster Zone Communication

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Abstract: When disaster-impacted areas have destroyed or inaccessible traditional communication infrastructure, it is important to find a dependable, real-time communication infrastructure in order to respond to an emergency and coordinate emergency response. This article suggests a real time wireless mesh network (WMN) scheme that is specially made to handle communications necessary in the disaster zone. The structure has a composite routing metric, which is calculated by using delay, residual energy and signal strength, in addition to real-time priority-based queuing mechanism. It provides prompt and trustworthy delivery of essential alerts, visual information and situation reports to the Emergency Operations Center (EOC). The given system is compared with the traditional protocols such as AODV and SafeMesh in terms of the NS-3 simulations with the different node density, traffic load, and failure rate. Experiments show significant performance gains: as much as 35 percent delay cut, 2025 percent energy consumption, and better reliability of packet delivery even in the presence of 30 percent node failures. The architecture assists in the energy-conscious route optimization and adaptive queue management in order to emphasize on urgent communications. The study proves the usefulness of intelligent WMNs as a reliable solution to emergencies. The next-generation developments might involve AI-assisted movement, the implementation of UAVs, and transmitted with blockchain security to be more scalable and secure.

1 INTRODUCTION

Within the past few years, the rate of occurrence of both natural and man-made calamities has gotten higher and more serious with severe devastation of important infrastructure, such as communication systems. The capacity to create effective two-way communication at any given moment, between emergency responders, medical staff, and the impacted community during crises becomes a lifeline in such crisis situations. The common forms of traditional communication systems like cellular network, a fiber optic and even satellite communications tend to experience traffic jamming, infrastructure breakdown, small area coverage or too costly to install in times of disaster. This has led to the focus towards more robust, self-healing, and infrastructure-free solutions such as Wireless Mesh Networks (WMNs).

The architecture of Wireless Mesh Networks provides a good emergency communication framework because it uses the capability to build decentralized multi-hop networks which can self-organize without using the infrastructure. Among the earliest studies on the viability of the distributed WMN in medical emergency response, Braunstein, et al. (2006) [1] showed that mesh-based communication systems could sustain the essential data streams when the conventional systems were taken over. In the same manner, Zhou, et al. (2021) [2] highlighted the usefulness of satellite-ground communication technology integration to regain connectivity after the disaster, but again, they have highlighted high latency and bandwidth constraints.

Although there are advanced technological skills, the current emergency communication systems can be affected by the performance constraints that are common in a harsh environment. In a comprehensive literature review of case studies on different communication infrastructures in an occasion of disaster, El Khaled and Mcheick (2019) [3] examined multiple cases. They emphasized on the fact that most systems do not ensure a satisfactory quality of service (QoS) particularly when the weather is extreme or when the infrastructure collapses. Carras, et al. (2022) [4] also echo these findings by evaluating the existing emergency technologies and found that no one of the systems cellular, satellite, sensor-based is a total solution on its own.

This is the area in which WMNs demonstrate unique strengths. The fact that they are flexible, scalable and can deliver localized high throughput communication makes them the best fit in dynamic and unpredictable disaster prone areas. Micheletto, et al. (2018) [5] suggested a real-time flying mesh network based on unmanned aerial vehicles (UAVs) coordination of the disaster relief in urban settings. Mobile nodes such as UAVs are useful in terms of coverage and flexibility, as well as the line-of-sight, particularly in congested locations. Conversely, battery-powered mesh node is of significant concern to energy efficiency in field applications. In response, Al-Hadhrami, et al. (2018) [6] proposed power-conscious routing protocols to extend the life time of nodes and at the same time deliver packets reliably, especially in an emergency situation where power is limited.

However, some gaps in research have not been filled. Most of the current protocols are not optimized toward real-time traffic particularly given the mobility and node failure. Wang, et al. (2023) [7] introduced an extensive background of emergency networks and highlighted the importance of multi-layered networks that support different data types and tolerate network failures.

Hence, this paper will discuss these issues by presenting a real-time wireless mesh network system to be used in disaster areas. The solution offered will be aimed at decreasing end-to-end latency, improving the energy-sensitive routing, and proving the delivery of messages according to priorities in the harsh environment. This research paper helps in sealing the gap between theoretical mesh network architecture and their application in real time emergency communication systems.

2 LITERATURE REVIEW

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Table 1: Comparative summary of key literature on WMNs for disaster communication.

Ref. No.	Author(s) & Year	Focus Area	Network Type	Contribution	Limitation Identified
[10]	Pirzada, et al. (2009)	Incident-area routing protocol	WMN	SafeMesh protocol	Lacks visual data support
[11]	Chai & Zeng (2019)	Context-aware hybrid routing	Hybrid WMN	Regional-aware protocol	Limited energy optimization
[12]	Pirzada (2008)	Emergency routing mechanisms	WMN	Route prioritization	Tested only in simulations
[19]	Carreras Coch, et al. (2022)	Tech review in emergencies	Mixed	Tech taxonomy, challenges	No new protocol proposed
[8]	Legesse, et al. (2025)	Energy-aware stable routing	MANET	Lifetime-focused algorithm	Not WMN-specific
[13]	Akyildiz, et al. (2005)	WMN fundamentals	WMN	Survey of protocols & models	Outdated with no IoT context
[14]	Al-Hadhrami, et al. (2012)	Visual mesh communication	Hybrid WMN	Real-time video transmission	Bandwidth bottlenecks noted
[15]	Ma & Chung (2022)	Wireless video transmission	Cooperative	Collaborative compression	No routing mechanism studied

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The increased relevance of energy efficiency of battery-powered mesh nodes has motivated a number of studies to optimize routing choices under energy constraints. The researchers Legesse, et al. (2025) [8] suggested a stable-path algorithm of AODV in mobile ad hoc networks, which would increase network lifetime based on remaining energy and path stability. Though it is concentrated on MANETs, the principles are applicable to WMNs that are applied in emergency situations. The literature review by Carreras Coch, et al. (2022) [9] was more comprehensive, and the researchers found that most emergency communication systems are power-intensive and do not exist without energy-aware optimizations.

Moreover, the incorporation of real time visual communication in WMNs has now become an essential need to first responders. A hybrid architecture of WMN was proposed by Al-Hadhrami, et al. (2012) [14], which supports real-time situational awareness by streaming video over the use of a multi-segment design. Their system had however bandwidth bottlenecks which may hinder mission critical communication. Ma and Chung (2022) [15] tried to address this issue by suggesting collaborative visual transmission scheme based on compression and control of redundancy. However, they were concerned with transmission performance but not routing flexibility.

Table 1 provides a comparison of these studies with their major contributions and shortcomings. It also identifies each reference based on focus area, type of network, significant innovations, and areas of weaknesses. As illustrated, although the current literature covers different aspects- routing, energy, video communication, none of the literature gives a comprehensive, real-time, energy efficient WMN framework specifically made to meet the needs of disaster zone.

3 METHODOLOGY

This part shows the architectural construction, routing scheme, energy modeling, real-time traffic scheme, and simulation background of the proposed wireless mesh network (WMN) framework to support disaster zone communication. The strategy is meant to provide real-time performance, energy efficiency, and quality of service (QoS) in understrained and dynamic conditions of emergencies.

3.1 System Overview and Architecture

The architecture suggested is the one that can be deployed quickly in the disaster zones where standard communication infrastructure can be destroyed or removed. It is composed of mesh nodes (i.e., rescue units devices, mobile UAV), intermediate routing units, and a central Emergency Operations Center (EOC). These nodes create an autonomy of healing, multi-hop network which can create routes dynamically with respect to signal strength, the availability of energy and priority of transmitted data. The block-level architecture is shown in Figure 1.

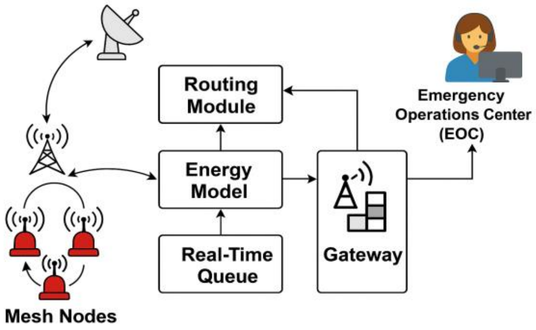

Figure 1: Block diagram of real-time wireless mesh network for Disaster Communication.

The node is composed of three internal modules, which include the Routing Engine, the Energy Estimator and the Real-Time Queue Manager [16], [17]. The information obtained via sensors or responder feedback is prioritized by urgency and passed through the optimized routes to the EOC or command gateway. Layered resilience is provided by a satellite or long-range fallback communication channel which is activated only after the mesh backbone reasons.

3.2 Routing Protocol Design

The optimal paths are chosen based on a composite routing metric to minimize delay, maximize signal strength and residual energy is taken into consideration. The measure is dynamically revised in every hop in order to capture the network conditions. The path scoring value is provided by:

$$R_{score} = \frac{w_1}{Delay} + \frac{w_2 \times RSSI}{H} + w_3 \times Energy_{residual}.$$

Where:

- Delay: estimated transmission delay;
- RSSI: received signal strength indicator;
- HHH: hop count to destination;
- $Energy_{residual}$: remaining node energy;
- w_1, w_2, w_3: tunable weight coefficients.

This measure is used to guarantee quality and timely transmission of data that is of high priority and time sensitive.

3.3 Energy Consumption and Node Lifetime Model

The nodes are powered by a very limited resource (battery or solar) and therefore, energy conscious choices are made in the routing logic. The power required per transmission is modeled as:

$$E_{total} = E_{tx}(k, d) + E_{rx}(k) + E_{idle}(t).$$

Where:

- k: packet size in bits;
- d: transmission distance;
- t: node idle time.

The distance and the environmental loss factors are the basis of determining the transmission and reception costs. The model is used to forecast node lifetime and develop energy balanced communication paths.

3.4 Real-Time Communication & Queue Prioritization

In order to facilitate real-time communication, a priority based queuing entity is established at each node. There are three types of incoming packets, including critical alerts, visual/media data, and routine updates. The delay of every flow is estimated as:

$$D_{total} = D_{transmit} + D_{propagation} + D_{queue}.$$

This delay estimation assists in deciding on rerouting high-priority packets through alternative lower-latency routes. Weighted Fair Queueing (WFQ) algorithm places critical packets at the head of the queue so that jitter and latency is minimized.

3.5 Simulation Environment and Configuration

NS-3 simulation are used to simulate with a 1000m 1000m disaster-stricken urban area. Nodes are using the Random Waypoint mobility pattern with varying speeds (15 m/s). Traffic contains live video (UDP), notification messages and regular data. Table 2 presents the key simulation parameters.

Table 2: Simulation parameters.

Parameter	Value / Range
Number of Mesh Nodes	20 – 50
Mobility Model	Random Waypoint
Traffic Types	Video, Alert, Data
Simulation Area	1000m × 1000m
Tx Power	0.5 – 1.0 W
Initial Energy / Node	1000 – 5000 J

Each of the simulations is repeated with 10 random seeds and the measures of the ratio of packets delivered (PDR), energy consumption, network lifetime, and end-to-end delay are measured.

3.6 Performance Evaluation Criteria

Performance is measured on the basis of:

- Latency: critical and non-critical data endtoend delay;
- Throughput: number of packets that have been delivered successfully in unit time;
- Energy efficiency: ratio of energy consumed/delivered per byte;
- Network lifetime: time taken to exhaust the energy of the first node.

Means and standard deviations are statistical values that are calculated between simulations to prove robustness. The proposed framework is juxtaposed to such baseline protocols as AODV and SafeMesh.

4 RESULTS AND ANALYSIS

In this section, the experimental assessment of the proposed real-time wireless mesh network (WMN) framework is performed in the conditions of simulated disasters. The performance has been compared using two base line protocols namely AODV and SafeMesh on different measures, which include delay, packet delivery ratio (PDR), energy efficiency and real time traffic management.

4.1 Delay Performance Analysis

In a disaster setup end to end delay is vital parameter of real time communication, especially in the case of alert messages and streaming information. The average end-to-end delay with respect to the size of the network is shown in Figure 2. The protocol offered always keeps the latency low at various node densities (20-50 nodes) and its value is slightly higher as the hops increase. Delay up to 50 nodes is minimal (68 ms) when sending critical alert compared to 115 ms and 102 ms in case of AODV and SafeMesh respectively. Low jitter and fast response times are guaranteed by the incorporation of weighted priority queue and real-time routing metrics.

4.2 Packet Delivery Ratio and Network Reliability

High resilience to node failures in delivering packets is a crucial element to mission-critical applications. The data in Figure 2 illustrates the ratio of packet deliveries (PDR) with respect to increasing node failure rates. The suggested approach can maintain more than 92% delivery success rate despite 30 percent of nodes failure whereas SafeMesh and AODV plummet to lower than 84 percent and 78 percent correspondingly. This is because it uses the adaptive route selection depending on the residual energy and quality of the linkage which enables the mesh to re-arrange paths dynamically. Figure 3 below provides PDR under Node Failure Rates.

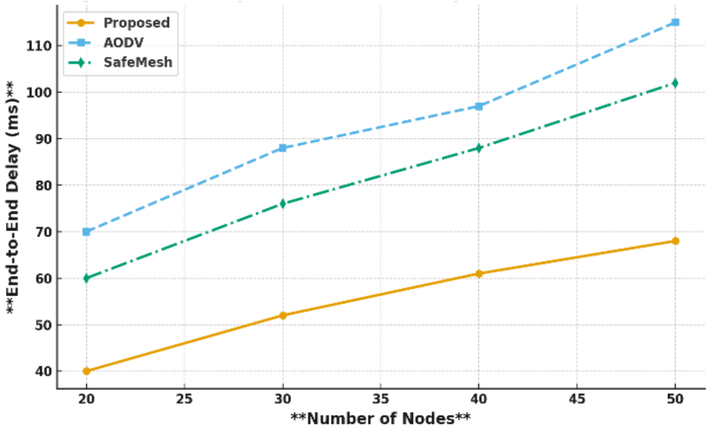

Figure 2: Average end-to-end delay vs number of nodes.

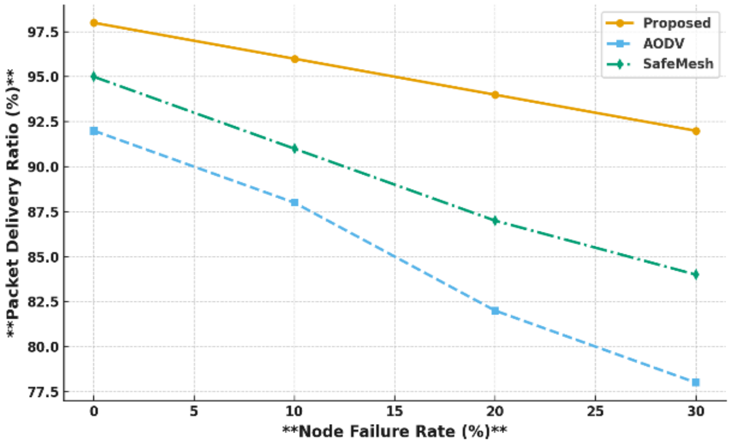

Figure 3: PDR under node failure rates.

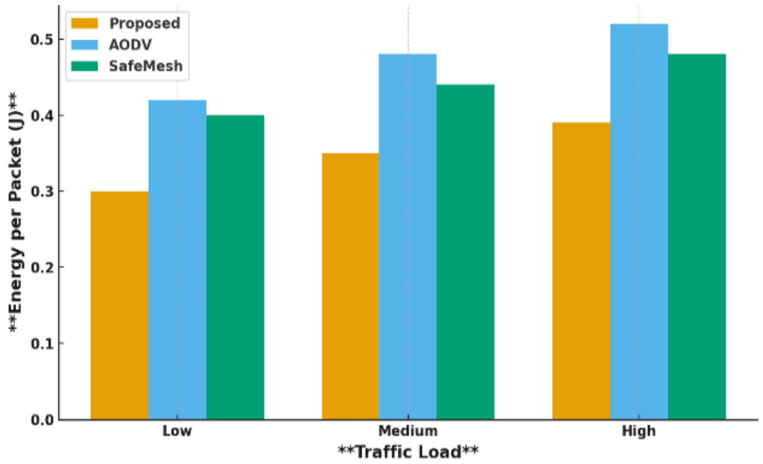

Figure 4: Energy consumption vs traffic load.

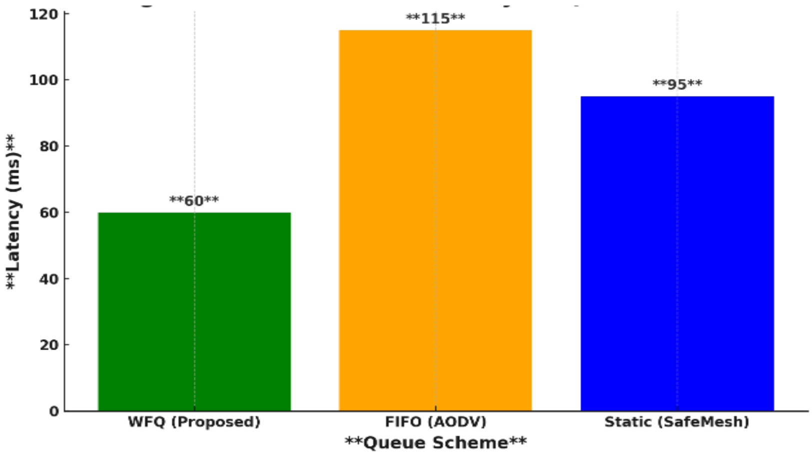

Figure 5: Critical alert latency vs queue scheme.

4.3 Energy Efficiency and Network Lifetime

Measures of energy consumption per packet are taken at varying loads of traffic. As it is depicted in Figure 4, the proposed protocol is better than both the baselines as it optimizes the routing routes to prevent the nodes that are exhausted of energy. In addition, Table 3 provides the summary of the comparative energy efficiency and estimated network lifetime. The proposed algorithm still only uses 0.39 J per packet and the node operation time is 2300 seconds, which is about a quarter of AODV.

4.4 Priority-Based Real-Time Performance

Under queue control strategies, the system is tested on the capacity to process emergency alerts with minimized lagging. The proposed protocol with the help of the weighted fair queueing (WFQ) has much lower delay of the critical alert packets than that of FIFO based on AODV and of static priority based on SafeMesh, as demonstrated in Figure 5. The delivery of critical messages takes 60 ms, and it ensures a fast situational awareness during the occurrence of a real emergency.

Table 3: Comparative energy and lifetime metrics.

Protocol	Avg. Energy (J/packet)	Network Lifetime (s)	Energy Saved (%)
Proposed	0.39	2300	-
AODV	0.52	1980	25%
SafeMesh	0.48	2050	19%

5 CONCLUSIONS

This paper proposed a real-time wireless mesh network (WMN) architecture for disaster-zone communication, designed to ensure reliable connectivity under infrastructure failure. The system combines a composite routing metric (delay, RSSI, and residual energy) with priority-based queueing to support emergency traffic differentiation.

Simulation results in NS-3 confirm that the proposed method outperforms AODV and SafeMesh in key performance metrics. It achieves lower end-to-end delay (≈68 ms at 50 nodes), higher packet delivery ratio (>92% under 30% node failures), and improved energy efficiency (0.39 J/packet). These results validate the effectiveness of the proposed approach for real-time communication in highly dynamic and resource-constrained disaster environments.

6 FUTURE WORK

Future research will focus on real-world experimental validation using physical testbeds and UAV-assisted mesh extensions to improve coverage in inaccessible areas. The integration of AI-based adaptive routing is planned to further optimize latency and energy consumption under mobility and high traffic load conditions. Additionally, security enhancements such as lightweight encryption mechanisms and blockchain-based trust management will be investigated to strengthen system resilience in critical emergency deployments.

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