iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: V Month of publication: May 2026

DOI: https://doi.org/10.22214/ijraset.2026.81635

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue V May 2026- Available at www.ijraset.com

A Comprehensive Survey on Decentralized Emergency Communication Frameworks: Bridging the Gap Towards Infrastructure-Independent Mobile SOS

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Abstract: In the aftermath of catastrophic events, the immediate collapse of terrestrial communication infrastructures critically hinders search and rescue operations during the vital "Golden Hour." While substantial research has explored ad-hoc networking, IoT meshes, and UAV relays to restore connectivity, many paradigms remain tethered to specialized hardware or cloud-synchronized control planes. This survey presents a thematic evaluation of recent advancements in decentralized edge communication, categorizing contemporary literature into clustering methodologies, multi-hop routing protocols, and resource optimization strategies. Through a rigorous gap analysis and a comparative study of eight state-of-the-art frameworks, this paper identifies critical systemic deficiencies in ubiquitous consumer hardware compatibility. We conclude by proposing MeshRelaya software-defined, energy-aware communication architecture utilizing native smartphone radios and a Gossip-based epidemic protocol to establish a self-healing emergency lifeline.

I. INTRODUCTION

The resilience of civilian communication systems is routinely compromised by natural disasters, leading to immediate cellular blackouts and internet fragmentation. In these infrastructure-void environments, the inability to transmit distress signals exacerbates casualty rates and paralyzes rescue coordination. Historically, mitigation has relied on temporary base stations, satellite links, or specialized LPWAN transceivers. However, these conventional fallbacks possess inherent limitations, including massive deployment costs and an architectural reliance on centralized nodes representing single points of failure.

Recent academic trajectory has shifted toward exploiting edge computing and device-to-device (D2D) architectures. Despite promising advancements in V2V, UWSNs, and FANETs, transposing these protocols to dynamic, pedestrian-carried smartphone networks remains a challenge. This paper reviews state-of-the-art literature to extract underlying methodologies and outlines the architectural blueprint for a viable, smartphone-centric alternative: MeshRelay.

II. THEMATIC LITERATURE REVIEW

To synthesize the current state of decentralized communication, the evaluated literature is categorized into three core operational themes: Topology Management, Data Routing, and Resource Optimization.

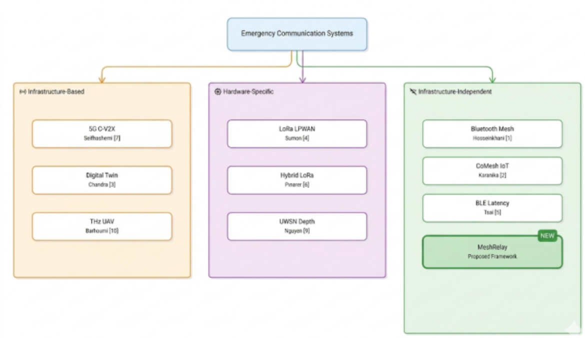

Fig. 1. Taxonomy of existing emergency communication frameworks categorized by infrastructure dependency

A. Topology Management and Clustering

Efficient network organization is fundamental to mitigating broadcast congestion and balancing energy loads. Researchers have increasingly utilized dynamic clustering to hierarchically structure edge devices. Sumon et al. [4] addressed wide-area sensor network longevity by proposing a multi-hop clustering algorithm formulated on mobility and real-time node metrics. Their approach dynamically calculates a fitness weight, incorporating residual energy and signal strength, to nominate cluster heads, utilizing a localized time-division multiplexing schedule to accelerate transmission slots. Similarly operating in challenging physical domains, Nguyen et al. [9] developed an energy-efficient, multi-hop clustering protocol tailored for underwater environments. Their architecture segments the network into vertical topological layers, dynamically assigning data aggregation or relay roles strictly based on a node's physical depth and residual energy, thereby significantly prolonging network lifespan. Transitioning from physical topologies to logical control planes, Karanika et al. [2] introduced *CoMesh*, an egalitarian, hubless architecture designed to decentralize sense-and-actuate workloads in IoT environments. By employing cryptographic sortition to establish localized "coteries" and executing ordered lock-acquiring protocols, the system bypasses centralized cloud coordinators to achieve dramatic reductions in computational overhead and bandwidth saturation.

B. Multi-Hop Routing and Data Dissemination

Once topologies are established, the reliable propagation of data across multi-hop links dictates the network's efficacy. Hosseinkhani et al. [1] investigated the feasibility of utilizing connectionless Bluetooth Mesh (BM) protocols for mobile environments. By relying on a managed flooding mechanism governed by caching and temporal limits rather than strict routing tables, their framework natively supported dynamic node mobility. In scenarios requiring inter-network communication, Pinarer et al. [6] proposed a multi-layered lifeline architecture. Their model captures localized smartphone data via short-range Bluetooth and offloads the transmission burden onto custom-built, peer-to-peer LoRa gateways, eventually routing packets to a cloud backend. Addressing high-velocity environments, Seifhashemi et al. [7] developed a resource-aware unicast routing protocol for 5G cellular V2V networks. Their algorithm preemptively circumvents network congestion by calculating relay paths that optimize both spatial progression toward the destination and the localized availability of cellular resource blocks. Pushing the boundaries of bandwidth capabilities, Barhoumi et al. [10] evaluated the deployment of multi-hop UAV relays operating within the unregulated Terahertz (THz) spectrum, proving that ultra-high capacity data streams could theoretically bypass destroyed terrestrial infrastructure if severe propagation losses could be mathematically managed.

C. Resource Optimization and Delay Mitigation

The final thematic pillar involves fine-tuning protocols to minimize latency and preserve finite battery reserves. Sadiq et al. [8] tackled the volatile link quality inherent to aerial networks by proposing a bio-inspired heuristic optimization model. Their framework continuously calibrates peer selection by mathematically balancing maximum throughput against energy conservation, utilizing dynamic fairness indices to prevent node exhaustion. In the context of localized device-to-device communications, Chandra et al. [3] introduced a Spatio-Temporal framework driven by a network "Digital Twin." By constantly monitoring spatial metadata and imperfect channel states on an edge server, the system dynamically adjusts transmission power to dramatically minimize the temporal degradation (Age of Information) of critical updates. Finally, focusing strictly on passive short-range radios, Tsai et al. [5] conducted a rigorous mathematical boundary analysis on delay-sensitive Bluetooth Low Energy (BLE) advertisements. They established optimal tuning parameters that synchronize scanning intervals with latency thresholds, proving that extreme energy conservation is possible without sacrificing real-time message delivery.

III. COMPARATIVE ANALYSIS

The following table summarizes the technical architectures and identified gaps of the reviewed literature.

Table I: Technical Comparison of Decentralized Networking Protocols

Paper	Primary Protocol	Hardware / Environment	Energy Strategy	The Gap (Failure in Mobile SOS)

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Paper	Primary Protocol	Hardware / Environment	Energy Strategy	The Gap (Failure in Mobile SOS)
[1] Hosseinkhani	Bluetooth Mesh (BM)	BMSim, Nordic nRF52840	Caching & TTL limits	Broadcast storms in dense crowds (>175 nodes)
[2] Karanika	Ad-hoc Wi-Fi, OLSR	Raspberry Pi 4 Model B	Cryptographic sortition	Requires specialized Pi hardware; not smartphone-ready
[3] Chandra	D2D Cellular	Digital Twin servers	Adaptive Power Control	Requires cloud-sync; fails in total infrastructure blackout
[4] Sumon	LoRa LPWAN	CupCarbon IoT Sim	Fitness Weighting	Low bandwidth (LoRa) fails in high-mobility scenarios
[5] Tsai	Connectionless BLE	Mathematical modeling	Optimized Scan	Low detection probability in dense areas
[6] Pinarer	Hybrid: BLE to LoRa	Custom LifeLink dongles	Static Gateway Offloading	Requires external, custom hardware dongles
[7] Seifhashemi	5G C-V2X Unicast	5G NR Radio Blocks	Resource-Aware Routing	Dependent on 5G Base Stations for resource allocation
[8] Sadiq	SAO-P2P (Heuristic)	UAV FANET Sim	Fairness Indexing	Heuristics too computationally heavy for mobile CPUs
[9] Nguyen	Layered UWSN	Underwater Sensor Sim	Depth-based Layering	Incompatible with 2D terrestrial pedestrian crowds
[10] Barhoumi	Terahertz (THz)	UAV Air-to-Ground	Sequential Quadratic Prog	Requires THz antennas not found in smartphones

IV. GAP ANALYSIS: THE BARRIER TO AUTONOMOUS MOBILE SOS

While the reviewed methodologies exhibit profound theoretical success, synthesizing them against the practical constraints of an offline, consumer-grade disaster scenario exposes severe architectural incompatibilities.

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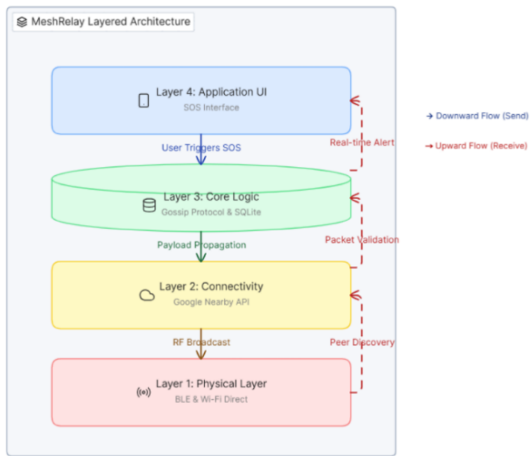
1) Hardware Exclusivity: A majority of the high-performance frameworks mandate specialized physical equipment. Protocols reliant on LoRa transceivers [4, 6], Terahertz antennas [10], or dedicated Raspberry Pi computation hubs [2] are entirely inaccessible to the average civilian trapped in a disaster zone, where the only available computational resource is an unmodified smartphone.
2) Infrastructure Dependency: Several "edge" solutions retain a fatal reliance on structural anchors. Methodologies requiring 5G Base Station resource allocations [7] or continuous synchronization with a Digital Twin cloud server [3] will experience catastrophic failure the moment wide-area backhauls are severed.
3) The Flooding and Complexity Trade-off: Purely decentralized approaches, such as mobile Bluetooth flooding [1], suffer from massive broadcast storms and rapid battery depletion in dense urban crowds. Conversely, highly optimized protocols utilize multidimensional heuristics [8] or fluid dynamic mapping [9] that are computationally too burdensome for mobile operating systems, or rely on mobility assumptions incompatible with chaotic, pedestrian movements.

Ultimately, the current literature fails to provide a lightweight, software-only framework capable of operating autonomously on heterogeneous, non-rooted mobile hardware without external gateway intervention.



V. PROPOSED SOLUTION: MESHRELAY

To decisively bridge the gaps identified in current literature, we propose **MeshRelay**, an infrastructure-independent communication framework engineered specifically for standard commercial smartphones. Moving away from hardware-exclusive LPWANs and cloud-tethered IoT meshes, MeshRelay is deployed entirely at the application layer, utilizing native dual-band Wi-Fi and Bluetooth Low Energy (BLE) antennas found in modern mobile devices.

The architecture abandons centralized clustering in favor of a highly optimized, decentralized **Epidemic Gossip Protocol**. To circumvent the broadcast storms endemic to traditional flooding [1], MeshRelay incorporates rigorous sequence-number caching and local database persistence (via SQLite), ensuring that devices never process or forward redundant data.

Furthermore, unlike computationally expensive heuristic models [8], MeshRelay achieves energy awareness through a lightweight Utility Scoring Function. Nodes evaluate their neighbors' instantaneous residual battery capacity and Received Signal Strength Indicator (RSSI) prior to delegating multi-hop routing tasks. Combined with Fig. 2. Proposed four-layer architectural blueprint of the MeshRelay framework.

an intelligent Time-To-Live (TTL) packet architecture and hybrid radio switchingusing BLE for passive, low-power neighbor discovery and Wi-Fi Direct for instantaneous, high-bandwidth payload transferMeshRelay provides a rapid, self-healing, and universally accessible lifeline for emergency SOS dissemination in absolute dead zones.

VI. FUTURE RESEARCH DIRECTIONS

Despite the robustness of MeshRelay, several open challenges remain for decentralized mobile SOS:

1) Security and Sybil Attacks: Developing lightweight cryptographic signatures to prevent malicious nodes from injecting "Fake SOS" messages into the mesh.

2) Cross-Platform Interoperability: Enabling seamless multi-hop relaying between Android and iOS devices using unified radio discovery protocols.
3) Multimedia Relaying: Optimizing Gossip protocols to support low-bandwidth image/voice transmission for visual site reporting during disasters.

VII. CONCLUSION

This survey confirms that while high-performance mesh architectures exist, they lack the "ubiquitous accessibility" required for civilian emergency response. MeshRelay represents a shift toward software-defined resilience, proving that existing smartphone hardware, when orchestrated through intelligent Gossip protocols and SQLite persistence, can form a viable, self-healing lifeline.

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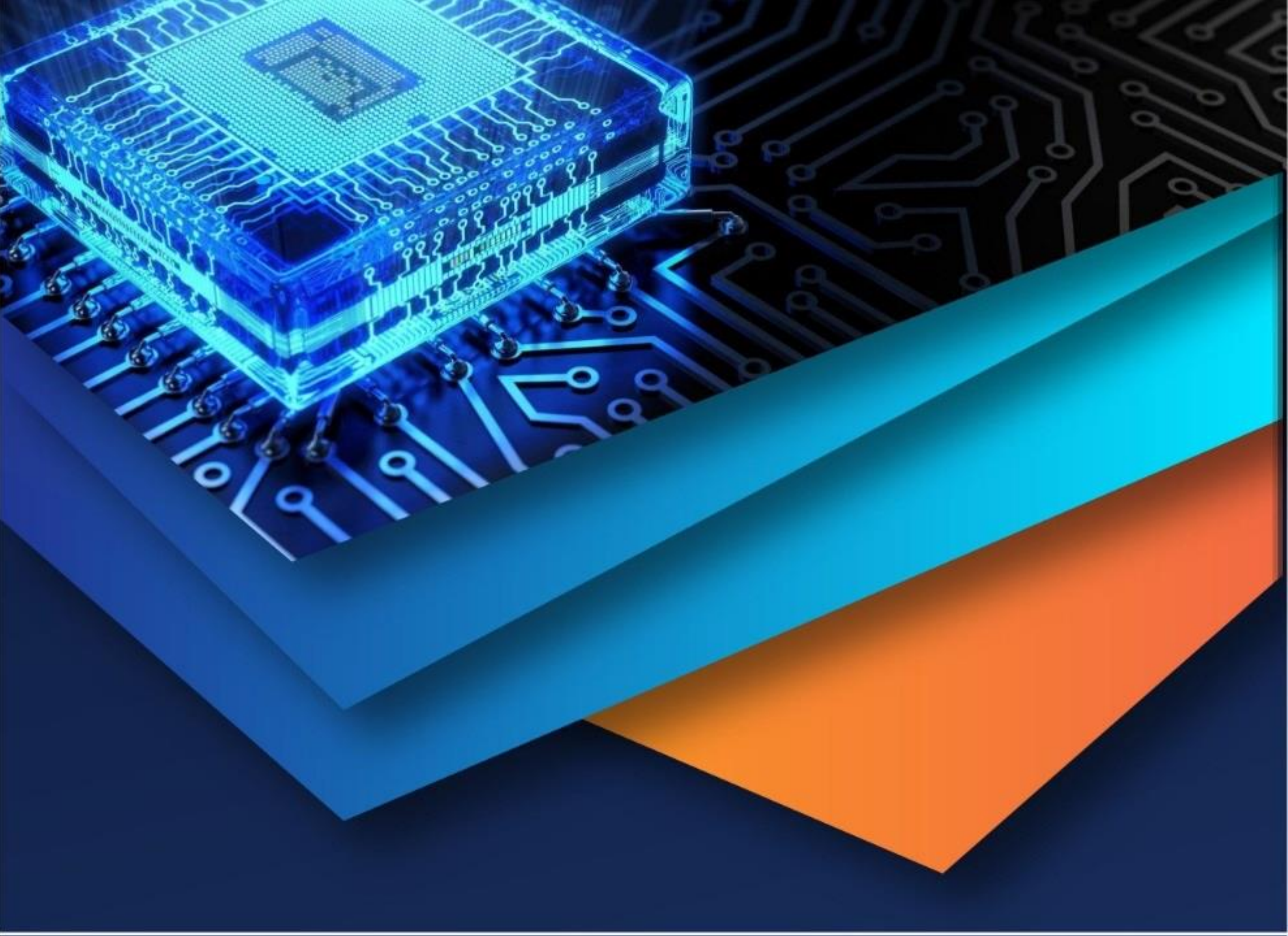

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