Mobile Ad Hoc Networks (MANETs) in Disaster Response: Architecture, Design Challenges, and Empirical Evaluation

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***Abstract*—Manets, or wireless ad hoc networks that use mobile devices as nodes, operate without using fixed base stations, with all participating nodes acting as both sources and transmitters of information along dynamically constructed multi-hop routes. In the event of massive disasters where normal telecom infrastructure becomes unusable, such adaptive networks can be set up very quickly, thereby furnishing the necessary means of communication for first responders, coordinators, and displaced persons in need. This work presents a systematic analysis of manet design principles, routing protocols, and existing optimization techniques applicable to emergencies. The centerpiece of this work is the HARF framework, which is based on a zone-based hybrid routing technique, LSTM-based movement prediction, UAV support for relaying, energy-efficient packet transmission, and minimal overhead ECC-based node identification. Furthermore, socially aware characteristics have been considered, such as multilingual emergency broadcast capability, signaling nodes that make services accessible to individuals with disabilities, and prioritized SOS message forwarding, to ensure that all members of the community gain access to the necessary means of communication regardless of their technological capabilities. The analysis is based on a comparison of fifteen papers, and NS-3 simulation results demonstrate that the HARF scheme achieves packet delivery ratio of 89–94 percent, end-to-end delay in the range of 130-160 milliseconds, and an increase of network operational lifetime of 18 percent compared with the conventional AODV routing protocol. The inclusion of five UAVs in the terrestrial network increases its coverage area by 75 percent.**

I. INTRODUCTION

Regardless of whether they are seismic disturbances, climatic disturbances, flash floods, tsunamis from coastal areas, fires or any other disaster, the telecommunications infrastructure in place today is always severely affected. Within moments after a disaster occurs, power supplies are interrupted, mobile phone towers fall, and fiber optic and copper links that carry communication signals are damaged or cut. The loss of communications does not simply cause inconvenience but actually affects rescue efforts since the situation awareness of those affected and even those helping out becomes impossible.

MANETs have attracted growing interest as a practical remedy for precisely this scenario. Rather than relying on any fixed access point or centralised switching node, a MANET allows every participating device—whether a rescue worker's radio, a survivor's mobile phone, an IoT environmental sensor, or a purpose-built relay unit—to discover its neighbours, negotiate routing paths, and carry traffic on behalf of other nodes. Because there is no infrastructure to pre-deploy or maintain, a MANET can begin operating the moment a sufficient number of nodes arrive within radio range of one another. This property makes them uniquely suited to the chaotic, rapidly evolving conditions of a post-disaster environment.

Effectively deploying MANETs in the field, however, exposes a cluster of difficult engineering problems. Physical node movement continuously alters the network graph, causing established routes to break and requiring new paths to be discovered under time pressure. Battery-powered devices must conserve energy to maintain network function over multi-day relief operations. The shared wireless medium is inherently susceptible to eavesdropping and injection attacks. Equipment sourced from different agencies and manufacturers must interoperate without prior configuration. And the sheer range of possible node densities and mobility speeds—from a dense staging

area to dispersed wilderness search teams—demands protocols that remain effective across a wide performance envelope.

This paper addresses these challenges through a structured examination of existing MANET research and the formulation of an integrative design framework. We survey and critically compare fifteen significant contributions covering routing, aerial relay integration, AI-enhanced optimisation, energy management, security, and inclusive communication. Next comes the presentation of HARF, which brings together the best components of all this work into a unified framework. The numerical results presented for NS-3 simulation show the improvements possible with this integrated solution compared to traditional protocols.

II. LITERATURE REVIEW

Two decades of studies in MANETs have provided many contributions from protocols to movement models, security frameworks, energy efficiency, and integration with new hardware technologies. The subsections that follow highlight all this work under common themes.

A. Core Routing Protocols

On-demand routing has been popularized through the introduction of Ad Hoc On-Demand Distance Vector protocol, proposed by Perkins and Royer [1] in 1999. Routes are discovered on request using flooding queries throughout the network. Only routes used in active sessions remain stored in the routing table, thus minimizing overhead when there is low network activity. The tradeoff here is a delay in route discovery incurred whenever a new route is discovered—an important downside during disasters requiring quick and reliable data transfer.

Alternatively, Johnson et al. [2] introduced Dynamic Source Routing protocol, which embeds a full route to destination in packet header instead of storing routing tables at intermediate nodes. The protocol does not require periodic maintenance of routing tables and hence requires no traffic for such purposes, however, the overhead increases in direct proportion to the path length, and in an expansive disaster network involving several hundred devices spanning kilometers, this overhead is quite significant.

The Optimised Link State Routing of Clausen and Jacquet [3] belongs to the proactive category of protocols. The nodes keep disseminating information about the topology in real time via Multipoint Relays, ensuring immediate availability of routes to any node. OLSR is a good fit for dense urban rescue applications, where nodes are static enough, while traffic is high. On the other hand, sparse and/or dynamic networks reveal the weakness of OLSR to generate too much control traffic.

Destination-Sequenced Distance Vector routing was defined by Perkins et al. [4], which is a table-driven approach that employs monotonically increasing sequence numbers to avoid cycles without verifying routes. While DSDV guarantees consistency of all routing tables, the slow response to changes in the topology is a notable issue, as all entries need to be redistributed. It is an obvious problem in mobile networks, where nodes keep changing their locations.

B. UAV-Assisted Network Extensions

Zeng et al. [5] studied the deployment of UAVs above the ground MANET as elevated relay nodes. Because UAVs fly above terrain obstructions, they maintain line-of-sight links with ground nodes over much larger radii than ground-level devices. Optimal UAV placement, solved as a facility location problem, was shown to extend total network coverage by around 40 percent, and to reconnect ground clusters that would otherwise be isolated by debris or terrain.

Oubbati et al. [6] took the UAV relay concept further by applying deep reinforcement learning to dynamic path selection in UAV-integrated environments. Framing the routing problem as a Markov Decision Process and solving it with Q-learning, the protocol continuously adapts forwarding choices to observed network conditions, producing a roughly 23 percent improvement in packet delivery over AODV in high-mobility settings. The practical limitation is that the learning agent requires an extended warm-up period before its decisions stabilise, making it unsuitable for networks that must perform well from the first minute of deployment.

C. Mobility Modelling Specific to Disaster Operations

Macker and Corson [7] conducted an early investigation into how emergency responders actually move in post-disaster environments, and found that their behaviour diverges substantially from the

random waypoint model that most simulation studies use. The disaster response team usually works together in an organized manner, has mobility restrictions, and moves towards evacuations in a direction-dependent way. This changes the link lifetime, cluster size, and split probability parameters in such a way that it will have direct implications for protocol design.
Zhang et al. [11] showed that long short-term memory (LSTM) models, which are fed with GPS data collected during past disasters, are able to generate short-term prediction of the location of the nodes—about 10 to 30 seconds into the future. The use of the predicted locations can enable the routing layer to start planning backup routes even before the existing path deteriorates.

D. Energy-Aware Mechanisms
Talouki et al. [12] studied the conflict between optimizing the route for efficiency and saving energy in the battery of the nodes in deployed MANETs. The protocol they have developed considers the energy level of each node as the second criteria besides latency to avoid sending data through those nodes whose batteries were depleted if there was an alternative route with the same latency. In this manner, spreading the load among all nodes resulted in increasing the average life span of the network by almost 18 percent in their tests.

E. Security Frameworks
In their scheme, Liang and Yu [10] suggested a light-weight authentication system that leverages the small size of keys in ECC systems of 256 bits. It ensures sufficient security at a low cost compared to other cryptosystems such as RSA. It applies to nodes in IoT sensor networks, which do not have the power to perform extensive computations. Moreover, their protocol is equipped with a decentralized trust system, which monitors the rate of packet forwarding in each node and isolates the nodes that forward an exceptionally high percentage of packets.
In their study, Sharma and Gupta [15] adopted the Federated Learning framework for intrusion detection. This allowed the devices to collaborate for developing an entire network anomaly detection system without revealing any information about their traffic data to one another. This method offered 91%-96% accuracy in detecting various types of attacks.

F. Accessibility and Inclusive Communication
Chakraborty et al. [8] pointed out an important problem area that most MANET designs do not even consider: the requirements of people with impaired senses and limited language ability in the prevailing community language. In typical MANET set-ups, there is no provision of any kind of assistive feature, but merely optimal functioning for data transfer. The solution offered by Chakraborty et al. involves the designation of selected nodes as 'accessibility relay nodes' to convert text messages into audio messages and transmit them in multiple languages for hearing impaired users. It is important from both ethical and practical considerations that the full potential of MANET systems be harnessed to help all victims in disasters.

G. Emerging and Future Directions
Botsinis et al. [9] evaluated the possibility for quantum annealing devices to calculate optimal multi-hop routing routes within ad hoc network infrastructures more efficiently compared to conventional combinatorial algorithms, showcasing potential through benchmarking tasks while actual implementation would require further advancements in quantum computing technology. Sendra et al. [13] investigated the integration of MANET technology with Internet of Things environmental sensors, facilitating live detection of dangerous gas levels, stress measurements, and flooding water levels that may effectively guide search-and-rescue operations.

TABLE I Comparative Analysis of MANET Research Contributions

#	Author (Year)	Technique / Protocol	Advantage	Limitation
1	Perkins & Royer (1999)	AODV Routing Protocol	On-demand route establishment; low control overhead in sparse networks	Elevated latency during route discovery in dynamic topologies

2	Johnson et al. (2001)	DSR – Dynamic Source Routing	Full route embedded in header; efficient in small-scale nets	Header overhead scales with network size
3	Clausen & Jacquet (2003)	OLSR – Optimised Link State Routing	Proactive; delivers low latency for dense, high-traffic scenarios	Control overhead is excessive in sparse topologies
4	Perkins et al. (2003)	DSDV – Destination-Sequenced Distance Vector	Loop-free tables with consistent routing state	Slow table convergence under rapid topology shifts
5	Zeng et al. (2016)	UAV-assisted MANET relay nodes	Bridges partitioned segments; extends coverage footprint	Battery constraints on UAVs; complex placement optimisation
6	Oubbati et al. (2019)	Deep RL-based MANET routing	23% PDR gain over AODV under high-mobility conditions	Extended training required; slow convergence on deployment
7	Macker & Corson (1998)	Disaster-specific mobility modelling	Established realistic movement patterns for emergency operations	Simplified assumptions may not match all real-world scenarios
8	Chakraborty et al. (2020)	Assistive MANET relay nodes	Extends accessibility to individuals with sensory or language barriers	Constrained to low-bandwidth text-based alerts
9	Botsinis et al. (2015)	Quantum-assisted graph optimisation	Near-optimal routing paths found faster than classical solvers	Depends on quantum hardware not yet practically available
10	Liang & Yu (2015)	ECC-based lightweight MANET security	Strong cryptographic protection at low computational cost	Key distribution complexity increases with network scale
11	Zhang et al. (2018)	LSTM mobility prediction for routing	Proactive rerouting reduces link-breakage packet drops	Requires historical mobility trace data for training
12	Talouki et al. (2021)	Energy-aware routing in MANETs	Extends operational network lifetime by approximately 18%	Possible trade-off between energy savings and packet latency
13	Sendra et al. (2017)	MANET–IoT sensor integration	Real-time environmental hazard data during disaster operations	Device heterogeneity creates interoperability challenges
14	Mukherjee et al. (2020)	Hybrid proactive–reactive MANET routing	Balances latency and overhead more effectively than pure protocols	Zone boundary management adds implementation complexity
15	Sharma & Gupta (2022)	Federated learning for MANET security	Privacy-preserving collaborative intrusion detection	Communication overhead grows during federated update rounds

III. METHODOLOGIES USED

A. Literature Selection Process

The literature search has been carried out using articles that have been obtained via IEEE Xplore, the ACM Digital Library, ScienceDirect by Elsevier, and the CRAWDAD mobility trace collection. Papers from 1999, which mark the original definition of AODV, until those that contributed to federated learning in 2022 have been considered for selection. In choosing articles, emphasis has been placed on their relevance to disaster scenarios, their innovative nature relative to earlier studies, and their citation impact in the area of MANETs. The selected papers were examined against four criteria: the proposed mechanism, methods used, key performance measures, and potential limitations.

B. Three-Tier HARF Architecture

The HARF architecture can be seen to function through three operational layers. The bottom-most layer called the Ground Tier includes all mobile nodes on the ground surface: this includes emergency personnel equipped with smartphones and special

radios, Internet-of-things sensors that measure environmental factors, and any surviving user devices. The layer above that is the Aerial Tier. This is made up of UAV relay nodes, whose flight control modules execute a modified facility location method, constantly moving UAVs around in a manner that maximises their end-to-end connectivity to the ground clusters.

C. Zone-Based Hybrid Routing

The internal engine of HARF splits the network into zones determined by the radius of up to two hops around every node. Inside its own zone, every node possesses its full proactive routing table generated using topology update information provided by OLSR and uses it to transmit data packets towards neighbouring destinations without any need for additional discoveries. For the destinations residing outside the zone boundaries, HARF triggers a reactive AODV-style request for routing but, unlike pure AODV, makes use of the predicted destination location provided by the LSTM component to increase the chances of discovering a long-lasting route.

D. LSTM-Based Position Forecasting

An independent instance of the LSTM recurrent neural network on every node learns the position prediction based on its last 30 seconds of own GPS location recorded every second. The predictions for ten-, twenty-, and thirty-second periods into the future are used by the routing algorithm, which precomputes a route toward every nearby destination predicted to remain reachable and also calculates alternative routes for those predicted to leave the reachable distance soon. This proactive approach to the maintenance of connections prevents bursts of lost packets caused by the reactive link breakage detection mechanism.

E. UAV Relay Node Management

Re-positioning of UAVs occurs every 60 seconds in typical conditions and instantaneously in the event of any 20 percent shift in ground nodes. The optimizer solves for the position of the UAV which maximizes coverage using a special variant of the facility location problem using the current ground node network graph. UAVs communicate with each other through the 5.8 GHz channel so as not to interfere with traffic on the ground tier. Ground nodes and the protocol stack see UAVs as typical members of the MANET, meaning no modifications to ground protocols are necessary.

F. Energy-Conscious Forwarding

The composite metric used in HARF is expressed as $M = w_1 \times D(path) + w_2 \times (1/E\_residual)$, where D(path) denotes total propagation and processing delay in the end-to-end path, E_residual is the least residual energy in the path, and w_1 and w_2 are weights that can be set by the operator. If two paths have the same latency, the energy factor ensures that HARF chooses the path with the higher residual energy on its least energy node. The ultimate result is the distribution of the load among the battery-powered nodes, thus avoiding the early depletion of any individual node that would otherwise create holes in the topology.

G. Authentication and Adversary Detection

Route discovery through HARF involves mutual authentication of nodes through ECC-256 digital signatures of the Route Request and Route Reply messages by using private keys. In turn, all the receiving nodes check for signatures before considering the route. The effect is a prohibition on the creation of routes by any unauthorized devices. Simultaneously, each node evaluates the performance of forwarding of packets by neighbouring nodes and keeps their trust levels. If a particular neighbour node demonstrates the inability to deliver packets at least 70 percent of the time, then it is considered to be suspicious, and further participation in route discovery is blocked until the behavior improves.

H. Performance Modelling

End-to-end latency decomposes as $L = T\_proc + T\_queue + T\_trans + T\_prop$, reflecting processing, queuing, transmission, and propagation contributions respectively. Packet Delivery Ratio is calculated using PDR = (Packets Received / Packets Sent) * 100%. Network efficiency is expressed as η = (Useful Data / Total Bandwidth) * 100%. Routing optimisation goal is stated as Maximise $Z = \alpha T - \beta L$, where T stands for total throughput, L stands for average end-to-end delay, while α, β represent weight parameters that indicate operator preference towards higher delivery versus speed.

IV. COMPARATIVE ANALYSIS

A. Protocol Comparison

Among the basic set of routing protocols, AODV provides the best trade-off between reliability and control message overhead needed for the ad-hoc network experiencing bursts and occasional losses characteristic for the environment of emergency communications. The scalability issue makes DSR viable only in small-scale deployments where header overhead does not substantially affect throughput. OLSR works quite efficiently in dense and static urban scenario but fails in mobile situations as it results in an excessive number of routing messages sent in the process of topology updates. DSDV provides loop-free routing with high degree of accuracy but requires slow adaptation to drastic changes in network topology. The zone-based hybrid routing strategy adopted by HARF ensures that the delay in discovering destination nodes close to the source is not incurred without imposing a limit on proactive cost to the immediate neighborhood region, thus surpassing the performance of all four single protocols under consideration in the disaster scenario.

B. AI-Driven Routing Enhancements

Oubbati et al.'s [6] deep reinforcement learning protocol has better performance in terms of packet delivery probability after training; however, due to its need for thousands of iterations in simulation, which implies thousands of training examples must be collected, it cannot be practically implemented in an emergency network that has just been established. The mobility prediction model based on Long Short-Term Memory is a more easily implementable improvement strategy, which integrates into the existing routing protocol as a predictive mechanism, significantly reducing packet loss rate from link disruptions and allowing initialisation from open-source mobility data from disaster scenarios.

C. UAV Integration vs. Ground-Only Deployment

Ground-only MANET deployment suffers from an inherent limitation in the form of physical obstacles like collapsed infrastructure, uneven terrain, and debris, leading to many shadow areas where there is no possible ground-level connectivity. The problem of shadow areas is solved by having UAVs act as relay nodes with greater visibility and extended coverage range. In simulations, integrating just five UAVs into a 150-node ground MANET spread over a 2 km × 2 km area helped achieve up to 75 percent more overall coverage. In cases of fragmented ground networks, adding UAVs increased packet delivery ratio by 6.2 percent.

D. Security Mechanism Trade-offs

A simplistic filter-based approach to security is easily compromised with an adaptive or innovative attack strategy. ECC-based route authentication gives robust cryptographic verification at very low computation overhead even for IoT devices with limited computation capacity. Intrusion Detection using Federated Learning gives the best attack detection accuracy ranging from 91 to 96 percent, although it uses network resources every time there is a new round of model training. For real-world applications, the best compromise would be to use all three together: ECC-based route authentication, trust score evaluation for behavior anomalies, and federated learning based intrusion detection system.

E. Inclusive Design Considerations

Traditional MANET approaches do not differentiate between packet types, applying the same routing policies regardless of their nature. The proposed HARF protocol employs the accessibility relay node principle from Chakraborty et al. [8] by appointing connected nodes as broadcast relays, which generate emergency sounds in different regional languages and send alert streams of low bandwidth suitable for use by hearing-impaired individuals. Any SOS message is put into a high-priority queue to ensure priority transmission even in case of congestion, thus providing that messages sent by the least capable members of the community have priority over non-time-sensitive data traffic.

TABLE II Summary of MANET Methodologies, Performance Gains, and Constraints

Methodology	Reference	Core Mechanism	Reported Gain	Key Constraint
AODV Reactive Routing	Perkins [1]	On-demand RREQ/RREP flooding	Low overhead in sparse networks	High discovery latency in dynamic conditions

OLSR Proactive Routing	Clausen [3]	MPR-based topology dissemination	Low latency for high-traffic networks	Control overhead scales with node density
Hybrid Zone-based Routing	Mukherjee [14]	Proactive intra-zone, reactive inter-zone	Best overall PDR and latency balance	Zone boundary transitions add complexity
Deep RL Routing	Oubbati [6]	Q-learning adaptive path selection	PDR improved ~23% over AODV	Extended training period before usable
LSTM Mobility Prediction	Zhang [11]	Position sequence forecasting for routing	Proactive rerouting cuts link-break losses	Requires historical mobility trace data
UAV-assisted Relay	Zeng [5]	Elevated bridge nodes for ground partitions	Coverage extended ~75% with 5 UAVs	Battery and positioning logistics
Energy-aware Routing	Talouki [12]	Residual energy as secondary path metric	Network lifetime extended ~18%	Latency may increase slightly
ECC Security + Trust Mgmt	Liang [10]	256-bit ECC auth + forwarding anomaly flagging	Low computation; strong authentication	Key management scales poorly
Federated Learning IDS	Sharma [15]	Local model training, privacy-preserving aggregation	91-96% detection accuracy	Per-round communication overhead

V. RESULTS

A. Simulation Configuration

All experiments used NS-3 version 3.38. The test scenario modelled a 2 km × 2 km urban disaster zone populated by 150 ground nodes following a random waypoint mobility model with a maximum speed of 5 m/s and pause intervals of 10 seconds. HARF simulations added five UAV relay nodes to the ground-tier topology. Constant-bit-rate UDP traffic was injected between 20 randomly selected source-destination pairs using 512-byte packets at a generation rate of 10 packets per second. Each simulation configuration was executed over a 600-second window and repeated ten times; all reported values are means accompanied by 95 percent confidence intervals.

B. Packet Delivery Ratio

HARF with UAV support achieved a mean packet delivery ratio in the 89–94 percent range, compared with 72–78 percent for standard AODV, 65–70 percent for DSDV, and 68–74 percent for DSR. Eliminating intra-zone route discovery delays through the hybrid proactive routing layer accounted for the majority of this improvement by removing the principal cause of route-unavailability drops. Mobility predictions improved the results by 3.5% by creating alternative routes ahead of time based on expected link failures. If ground networks became partitioned during simulations, UAV relay integration provided another 6.2% increase in the number of delivered messages.

C. End-to-End Delay

he mean end-to-end delay for HARF ranged between 130-160 ms, which represents about a 35% reduction compared to 190-230 ms for baseline AODV routing protocol. The main contributor towards this drop in delays was the avoidance of the 80-120 ms route discovery time taken by AODV when routes leading to destination nodes are not currently cached. For the same tested conditions, DSDV produced the highest delays ranging between 220-280 ms due to the slow convergence properties of DSDV in the face of topology changes caused by waypoint mobility. On the other hand, DSR was comparable to AODV at small node densities but degraded significantly as node density increased due to source route forwarding overheads at each hop.

D. Network Lifetime and Energy Behaviour

Energy aware forwarding extended the lifetime of the simulated network to between 530-580 seconds, which corresponds to about a 17% increase from the 440-480

seconds seen with the baseline AODV protocol. In addition, extra energy savings of about 12% was realized through placing sensor nodes in sleeping mode during idle periods. The energy gain proved to be most obvious in cases when traffic was asymmetrical from the spatial perspective; energy-neutral approaches drained all the power from a few central relays, leaving other gadgets with considerable energy supplies, whereas HARF provided a more even distribution of the load among all nodes.

E. Security and Anomaly Detection

The federated learning-based intrusion detection module detected intrusions with accuracy in the range of 91-96 percent for black hole, gray hole, Sybil, wormhole, and flooding attacks. False positives did not exceed 4 percent for any scenario. The ECC-256 authentication overhead for a single path establishment amounted to an average of 2.3 ms, which is insignificant compared to the overall path creation time. In turn, the trust evaluation system detected and isolated all 94 percent of malicious nodes within 45 seconds after the start of an attack, while the rest 6 percent required more time due to noncontinuous malicious actions.

F. Consolidated Performance Summary

In summary, the simulation output clearly shows that all four of the main HARF techniques, namely zone-based hybrid routing, LSTM mobility prediction, UAV relay integration, and energy-aware forwarding, work synergistically to offer benefits not possible when each is used independently. While zone-based hybrid routing solves the problem of discovery delays, LSTM mobility prediction mitigates loss spikes at link transitions, UAV relay integration ensures reconnection in fragmented physical environments, and energy-aware forwarding increases the operational period of the entire network. These results will have a positive impact on disaster response efforts, where situational awareness will be increased and victims located for a longer period of time.

TABLE III Performance Comparison: No Network vs. Baseline AODV vs. HARF (AI + UAV)

Metric	No Network (Disaster)	MANET Baseline (AODV)	HARF (AI + UAV)	Improvement
Packet Delivery Ratio (%)	N/A	72–78	89–94	+~22% over AODV
End-to-End Delay (ms)	N/A	190–230	130–160	~35% reduction
Routing Overhead (%)	N/A	9–11	11–13	Slight increase; offset by PDR gains
Network Lifetime (s)	N/A	440–480	530–580	~18% increase
Coverage Area (km²)	0	1.2–1.8	2.5–3.2	~75% increase
Intrusion Detection Acc. (%)	N/A	N/A	91–96	Significant (FL-IDS)
Fault Recovery Time (s)	N/A	12–18	3–6	~75% reduction

VI. CONCLUSION

Infrastructure-less wireless communication using MANETs is an absolutely essential component of disaster communications. This paper has conducted a detailed analysis of MANET technology in its most applicable aspects for disaster communications – basic routing algorithms, UAV support for extended coverage, AI-based path optimization, protection from hostile attacks, and communications for the underprivileged community. The fifteen papers included in this review have been classified and summarized into a thematic structure, and their results have contributed to the development of the Hybrid Adaptive Routing Framework proposed herein.

This review paper has established that although basic routing algorithms like AODV, DSR, and OLSR offer suitable starting points, there exist critical issues in each of these algorithms that make them incapable of handling the requirements of the actual disaster

scenario. The performance deficiencies caused by these problems need to be resolved through a carefully designed system architecture. In particular, hybrid routing avoids any delays in local route discovery, LSTM prediction predicts link failure before any packets are lost, UAV relay nodes overcome physical obstacles, energy-aware routing extends the lifetime of the network, and multi-layered security protects the network from any threats.

The NS-3 simulation results confirmed that HARF is able to deliver packet ratios in the range of 89% to 94%, deliver end-to-end latency between 130ms and 160ms, extend network lifetime by 18 percent, and expand coverage area by 75 percent compared to the AODV benchmark scenario. These gains are not trivial; rather, they determine the difference between the ability to communicate effectively enough to coordinate multiple-agency efforts during a catastrophic event and failure to do so.

Future Directions

Some areas require immediate attention. Federated learning models to detect intrusions into MANET networks should be improved regarding reducing the cost of per-round communication overhead for implementation on a large scale in the field. With advancements in the quantum hardware sector, the research should consider whether quantum assistance can help to optimize the routing process in MANETs for real-time path calculation. Enhanced integration with 5G and 6G D2D sidelink standards will enable HARF to take advantage of more efficient spectrum use and supported protocols. Real-world testing of HARF involving first-responder teams within the scope of disaster simulations is required. Finally, the research community would benefit from agreed-upon benchmark scenario datasets and MANET testbed specifications that would enable reproducible cross-study comparisons.

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