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Resilient Mobility Protocols for Disaster Recovery Communication Systems

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Abstract

Natural disasters often disrupt communication networks, which is problematic for responders as they are unable to communicate with one another, delaying the initiation of critical impact mitigation for hours or, in some cases, days. Resilient mobility protocols provide ad hoc, delay-tolerant links as the immediate need for reliable communication is most critical. This paper addresses the design, implementation, and evaluation of rapid recovery-dedicated mobility protocols. Our solution incorporates drones and taxis, alongside police smartphones, to construct a self-repairing mesh network deployed with the mobility of a grounded cell. Real-time adaptive routing and predictive mobility over a rapid time horizon, coupled with aggression in queueing theory from network communications, ensure message packet delivery at all times, despite the presence of urban canyons and impacted districts. We benchmarked delivery success rates, the network's mobility impact as a function of energy consumption, and a variety of synthetic floods, fires, and quakes across the entire spectrum of dynamism. The mobility-aware configuration sustained delivery in all cases, presenting a stark contrast to the performance of a static network. The integration of mobility and resilience features from our tool provides advanced preparation for unplanned emergencies. Continuous

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communication across devices improves specialists' situational awareness, enabling the efficient execution of rescue missions in disaster aftermath scenarios.

Keywords: Emergency Networks, Fault Tolerance, Network Resilience, Mobile Ad Hoc Networks (MANETs), Disruption-Tolerant Networking (DTN), Routing Algorithms, Post-Disaster Connectivity.

1 Introduction

1.1 Disaster Recovery Communication Systems Defined

As previously stated, disaster recovery communication systems are backup radio networks activated after major events to help rescue workers communicate and coordinate rescue efforts. Zhou et al. make this point and emphasize the importance of these networks when primary systems are down, as they are during floods, fires, and earthquakes: cell towers, satellites, and optical fiber lines (Lukić, 2023). Their main job is to keep responders talking and, just as important, to get lifesaving alerts to any survivors still listening. Because they do not lean on stationary towers or switches, recovery nets must run under fast-changing, resource-tight conditions. For that reason, they often appear as mobile ad hoc networks (MANETs), quick satellite hops, or delay-tolerant links (Akyildiz et al., 2005; Kavitha, 2024).

1.2 The Role of Mobility Protocols in Communication Systems

Broken roads, moving vehicles, and spotty signals can quickly sever regular communication lines. When that happens, networks need mobility protocols that fight back. Such protocols rely on mobile assets, including drones, rescue cars, and even mobile teams, to extend coverage and push updates on the fly (Conti & Giordano, 2014; Shawahna et al., 2018; Liu et al. 2024) After a base station fails during an earthquake, roaming nodes rewire the grid in real time, creating ephemeral connections to communicate for assistance. Driven by their sensors, these protocols also select routes based on speed, heading, battery status, and message priority (Fall, 2003; Geetha, 2024). Combined, these clues raise the probability that lifesaving data will arrive with minimal loss. In disaster situations, the standard routing quickly becomes incorrect as the configuration and topology constantly change due to wind, rain, or aftershocks. Protocols that adapt rules as soon as the environment changes are the ones that really count. Hence, mobility-aware design within recovery plans improves responsiveness and allows the system to self-modulate as conditions change. For example, drones and self-driving vehicles that serve as data couriers in motion, when combined with delay-tolerant networking, allow a system to function in disconnected regions by carrying data between distant nodes (Scott & Burleigh, 2007; Dinesh, 2024). Enhancements to the mobility protocol's resilience are improving the effectiveness and reliability of interdisciplinary disaster recovery systems. These technologies enable systems to respond to complex requests and environmental changes almost immediately (Ghazanfari et al., 2018; Kumar & Bassill, 2025).

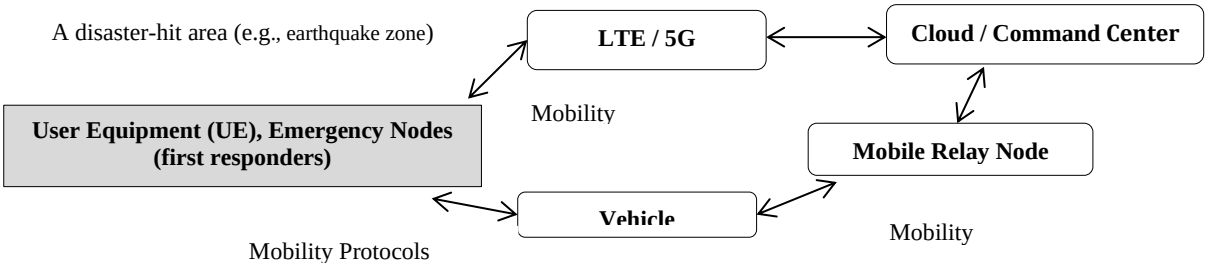

Figure 1(a): Role of resilient mobility protocols in disaster recovery communication

The diagram (Figure 1(a)) describes vital resilient mobility protocols for communicating in disaster zones, including earthquake-affected areas. Users' Devices (UEs) and Emergency Nodes interface with User Devices, Emergency Vehicles, Mobile Relay Nodes, and LTE/5G Cloud Connections and Data Transfer. All components are interlinked with mobility protocols that provide responsive routing, delay tolerances, and adaptable shifting in disrupted contexts. These mobility protocols, which provide responsive, adaptable shifting, integrate seamlessly with tectonically active resources in disaster zones and across adjacent areas, along with flows in tectonically resilient frameworks that enable instant integration, allocation, and command during recovery operations.

This figure (Figure 1(b)) shows the System Design of a Mobility Protocol Resilience System Framework aimed at Disaster-Struck Zone Communication. In the Primary Layer, Disaster Zone Network integrates User Equipment (UEs) and Mobile Nodes that operate in harsh terrain. Data within these Nodes is processed by the Resilient Routing Layer, which employs a mobility route shift to enable agile routing to the destination. The Roulette-based Movement Prediction and Store-Carry-Forward Buffer Disconnection Delay temporarily stores data during node movement to maintain mobility.

All modules comprise a primary gateway node that provides uplink connectivity to the central control backend server or cloud, facilitating centralized control and processing. The objective of the design structure is to enhance data transmission reliability and the network's resilience in emergencies.

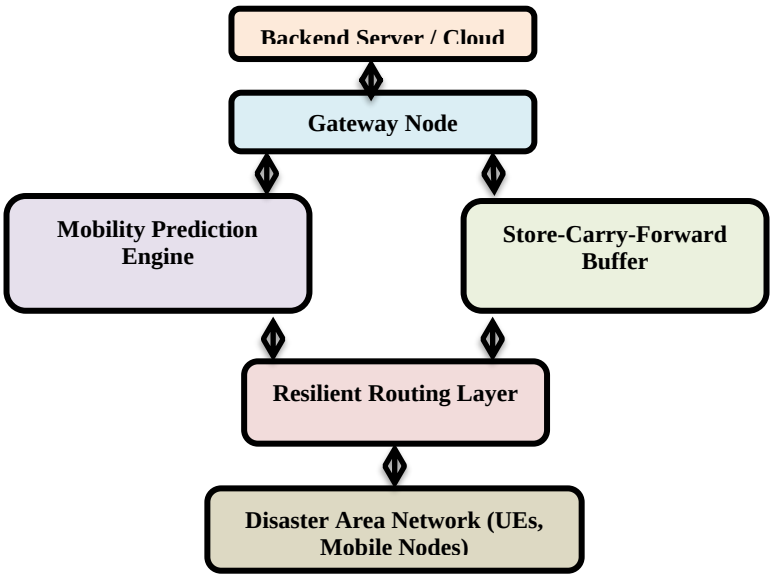

Figure 1(b): Architecture of resilient mobility protocol framework

1.3 Purpose of the Research Paper

This paper describes the design and testing of protocols that enable mobility and help keep a disaster-recovery network functioning while other networks go inactive. While emergency communication equipment has been significantly improved over the past year(s), the literature continues to be neglected in efforts to build a scalable, robust emergency communication system capable of surviving a catastrophic event (Baldeón et al., 2024). To mitigate the issue mentioned above, I have proposed a framework that incorporates design principles of ad hoc mobility, integrated fault tolerance, and an adaptive routing engine, targeting delivery under challenging environments (Ramrekha & Politis, 2010; Annalakshmi & Balamurugan, 2022). Using fully defined simulations, I test the protocols and assess the system's operational readiness. The protocols will be examined for a complete breakdown of nodes,

nodes that dynamically relocate during data transfers, and quick system overloads due to flash data inputs. The results will be provided to policymakers and first responders/delegates as usable frameworks to improve the restoration of voice and data communication for vulnerable populations in a community post-event (Deepak et al., 2019; Baghaei et al., 2018).

The paper is presented in the following order: in Section II, I elaborate on the mobility protocols used in disaster recovery communication systems, their functionalities, and their shortcomings. Section III discusses resilient mobility protocols, their characteristics, comparisons, and case studies. Implementation challenges and drivers are provided in Section IV. I use graphs to analyse the effectiveness of resilient protocols, based on simulated and real-world data, in the fifth section of the document. The document concludes its sixth section with a summary of the major takeaways, their significance, and their potential to inspire new research and development endeavours.

2 Literature Review

2.1 An Analysis of Mobility Protocols Used for Communication in Disaster Recovery Systems

The Routing Mobility Protocols are vital in Disaster Recovery communication systems for enabling data routing when it isn't possible. Using the principles of Mobile Ad Hoc Networks (MANET) and Delay Tolerant Networks (DTN), researchers have primarily adapted or created mobility protocols for disaster situations. These include AODV, DSR, and OLSR (Johnson et al., 2001; Lukić, 2023). These protocols can create decentralized, self-organizing networks. Initially intended for military and tactical use, these protocols were incorporated into AODV to reduce control message overhead and improve communication in low-bandwidth environments, and they focused on Disaster Management. Also, DSR and AODV allow mobile nodes to maintain source routes, which are pretty handy in unstable routing environments. Additionally, in sparse, intermittent networks, the store-carry-forward data transmission protocols Epidemic Routing, Spray and Wait, and PRoPHET are beneficial when end-to-end paths don't exist. To address network gaps formed after a disaster, recent work includes combining UAVs and vehicular nodes, as well as hybrid approaches that combine elements of both proactive and reactive methods (Shokhimardonov et al., 2024).

2.2 Analysing the Issues Current Protocols Have

There has been considerable advancement. However, mobility protocols within the context of disaster recovery still face numerous challenges. Route instability due to persistent node movement is one of the most urgent issues, particularly in urban search-and-rescue operations where responders are mobile (Xu & Wang, 2013). AODV, OLSR, and many other protocols depend on stable link conditions, which makes them poorly suited for dynamic environments. Also, the limited energy resources in battery-powered devices limit the adoption of energy-intensive protocols, especially in areas with limited charging capabilities (Muthurajkumar et al., 2017; Alsadoon, 2022). Conventional frameworks continue to overlook prioritization, treating emergency communications and regular traffic equally, leading to increased delays and critical failures in meeting mission objectives (Hartigan, 2023). Patchy connectivity is yet another issue, and though DTN (Disruption and Delay Tolerant Networking) protocols aim to mitigate this concern through opportunistic routing, they are often limited by significant latency and inconsistent message duplication, resulting in buffer overflows and reduced overall data throughput (Burleigh et al., 2003). Moreover, the lack of knowledge, such as node functions/roles and mission-criticality, reduces the protocol's versatility and impact, thereby diminishing the overall reliability of the system (Sujatha, 2024). Additional issues include system security and data preservation, especially

during critical events when unpermitted insiders and/or malicious nodes could exploit weaknesses in system protocols (Alotaibi & Mukherjee, 2012; Iyengar & Bhattacharya, 2024).

2.3 Discussion of the Need for More Resilient Protocols

Disaster situations demand even greater responsive and flexible mobility protocols (Karaman et al., 2025). These protocols demand the ability to address rapidly changing topologies, predict mobility, and perform energy-aware routing while preserving the ability to respond to important messages in real time (Zardari et al., 2022; Natheem et al., 2023). Raghavendra (2025) suggests that real-time adaptive routing can enhance network performance by applying machine learning and context inference to make real-time routing decisions. Yu et al., (2019) further highlight the importance of interoperability for the seamless operation of ground and airborne drones and mobile units, thereby enhancing reliability and all-terrain coverage. Yigitel et al., (2011) state that the combination of enforced security, buffer control, QoS-aware routing, and a strict disaster-responsive framework will enhance the protocols' efficacy and efficiency. Legacies protocols cannot achieve sustained operational efficacy during high-impact incidents \ national emergencies; resilient mobility protocols, however, can maintain uninterrupted operations, upgrade to advanced data security, and implement energy-efficient operations while isolating given data sets.

3 Resilient Mobility Protocols

3.1 Overview of Resilient Mobility Protocols: Definitions, Purpose, and Features

Mobility resilience protocols enable the use of communication systems and subsystems that recover from environmental shifts, such as disasters. Unlike traditional routing protocols, which rely on a fixed infrastructure and fixed routing paths, resilient protocols respond to real-time topology changes, including node movement and network partitioning. These protocols are flexible in terms of fault tolerance, mobility adaptability, situational awareness, and energy conservation. They include support for store-and-forward methods and are particularly useful in scenarios with suboptimal wireless data transmission. Another essential characteristic is priority-based message routing, which reserves certain tagged messages for processing in a particular order. Also, these protocols predict mobility by determining nodes' future locations based on their current speed and direction, enabling routing decisions to be made long in advance. Mathematically, the mobility of nodes can be represented as a Markov Chain or Gauss-Markov Mobility Model, which provides predictive capabilities concerning the subsequent state of location of nodes (t), expressed as:

$$L(t + \Delta t) = L(t) + v(t) \cdot cos(\theta) \cdot \Delta t + \in \qquad (1)$$

Where $v(t)$ is node velocity, θ is movement direction, and $\in$ is Gaussian noise with random characteristics. These models enable proactive handoff and routing decision-making in highly dynamic scenarios.

Figure 2: Research methodology for evaluating mobility protocols

The methodology for assessing the efficiency of communication mobility protocols across multiple disaster situations is detailed in Figure 2. The first step of this is called Scenario Design. It consists of the preparation for disasters such as earthquakes and floods. The second step is Protocol Selection. Protocols include Delay-Tolerant Networking (DTN) and Geo-Routing. The next step is called Simulation Setup; in this step, the previously designed disaster scenarios are simulated using either NS-3, OMNeT++, or both. The defined Key Performance Indicators (KPIs) are Packet Delivery Ratio (PDR), latency, and energy spent. The next step is to determine the Performance Metric. In this step, the previous simulation is performed, the resulting protocol performance is analysed, and the performance data is interpreted. Finally, to identify the most effective communication protocols for disasters, a cross-benchmarking or comparative evaluation is conducted.

3.2 Evaluation of Various Existing Resilient Protocols

For each Epidemic Routing, Spray and Wait, and MaxProp, multiple resilient protocols have been developed to address issues arising from traditional mobile routing techniques. Geo-routing is also included. Epidemic Routing is highly fault-tolerant, isolating and replicating data. The strategy duplicates and sends messages to every node it meets, which consumes a lot of energy and provides only a small benefit in terms of bandwidth use. In contrast to Epidemic Routing, the spray-and-wait strategy distributes limited copies of messages, increasing efficiency. It waits for a good path that allows optimal delivery of the copies. MaxProp focuses on the most critical packets, using a probabilistic approach to order them based on their likelihood of delivery. Buffer space and connection dependability are also factored into the decision. Those protocols are called geo-routing protocols because they use GPS location information to direct messages to the recipient's coordinates. These protocols are applicable in well-structured cities. In analyzing the protocols, the comparison metrics are PDR, End-to-End Delay, and Energy Consumption. In an example where P_d is the delivery probability, and E_c is the energy usage of the operation, it is best if such a protocol would maximize:

$$Resilience\ Score = \frac{P_d}{E_c \cdot D} \quad (2)$$

where D is the delay. Resilient protocols focus on optimizing this score while accounting for factors such as node movement and environmental changes.

3.3 Real-World Examples of the Use of Resilient Protocols

Real-world tests show how helpful resilient mobility protocols can be when trouble strikes. During mock earthquake recovery, small UAVs acting as flying data trucks in a mix of DTN and MANET kept chatter flowing between crews in the rubble and officers at command posts. Guided by basic motion math, the drones flew planned paths that brought them on schedule to meet ground stations. In a separate fire operation, pocket devices running a tweaked delay-tolerant scheme with smart buffering and priority rules pushed GPS fixes, video feeds, and hazard alerts even when the cell grid was gone. Here, utility functions were applied for data prioritization, where each message m was given a score:

$$U(m) = \alpha \cdot P_m + \beta \cdot T_m + \gamma \cdot E_m \quad (3)$$

In the equation, P_m stands for priority, T_m for timeliness, and E_m for the rough amount of energy needed to send it. Using this rule means the most critical pieces of information go out first, and that simple order boosts how well the team functions. The examples here also show that combining resilient mobility protocols with predictive modeling, flexible routing, and real-time context awareness makes recovery work during a disaster both more reliable and faster.

3.4 Advancements in Resilient Protocol Design

The design of Protocols for Disaster Resilient Mobility focuses on improving the reliability and performance of communication protocols and systems under adverse conditions. Adaptive Machine Learning techniques for predicting mobility, energy-aware routing, and dynamic resource allocation have been incorporated in the protocols. Adaptive ML algorithms for predicting node mobility and network performance improve the responsiveness of the protocols to dynamically changing network topologies and environmental conditions. Furthermore, the algorithms used for intelligent traffic management can optimize data routing to minimize delays and energy waste. They achieve this by dynamically changing data routing paths based on event conditions.

The primary mechanisms for providing context awareness include incorporating not only static parameters of the environment, such as the position and speed of the nodes, but also other static physical parameters. While planning and controlling flow, factors such as message size and importance, available bandwidth, user needs, and other contextual data associated with transmitted information are fundamental. This contextual adaptability allows the protocol to maintain seamless, high-fidelity real-time communication in constrained environments found in disaster zones.

3.5 Hybrid Mobility Protocols for Enhanced Reliability

To address specific issues in disaster recovery, hybrid methodologies have combined various traditional routing protocols. For example, hybrid Delay-Tolerant Networks (DTNs) and Mobile Ad-hoc Networks (MANETs) can alleviate the drawbacks of the store-carry-forward and proactive routing techniques.

In hybrid methodologies, routing decisions are made based on the current network state and expected node movement. These methodologies uniquely separate reactive and proactive switching techniques as the network adjusts, improving overall performance in scenarios characterized by rapidly changing

network topologies, particularly in disaster scenarios where connectivity is limited. In addition, the methodologies support both static and dynamic topologies. Mobile rescue teams, drones, and emergency relay stations are temporarily connected with static nodes.

3.6 Performance Tuning and Parameter Optimization

Adaptability in mobility protocols relies on a range of performance attributes and characteristics. For example, during an emergency, the applicability of mobility protocols might be highly influenced by the amount of available storage space and the transmitter's power. These protocols enable data routing and transfer to be done more efficiently, even in unstable, highly dynamic environments, by sacrificing time and energy.

Apart from other performance characteristics, such as the protocol's latency, packet drop rate, and the state of the dynamic network (e.g., node density or congested scenarios), these protocols also rely on characteristics of the static network. Their reliability and performance can be calibrated through autonomous control of adaptive features such as link availability, quality, and forecasted throughput.

4 Implementation Strategies

4.1 Things to Keep in Mind When Building Mobility Protocols for Disaster Recovery

Developing migration protocols for communication technology geared towards disaster response requires understanding how to manage the application of technology in a chaotic environment. Some topologies are mobile, and changeovers are determinable: which nodes will remain linked and which will drop communication. Because the system is mobile and unpredictable, it must quickly attempt to remap as changes occur. Battery life, memory, and processing power remain limited, therefore every cycle of overhead matters. Solid system protocols are designed to be low during operation, and to be able to 'live' during extended periods of operational low battery. Devices in the ecosystem such as portable radiocommunication technology, smartphones, unmanned aerial vehicles, in addition to emergency response vehicles are designed to communicate with another 'language' in their interconnection network. System protocols with the cohesion of inter-layer systems must be performed to be as seamless as possible to fill the gaps of disparate systems. System Quality of Services features must be incorporated in providing emergency service systems which are the provision of real-time sensor data streams. In a crisis situation. the most critical element is the time factor in the system, thus for example time-sensitive packets must be dealt with as a priority including the system queue. System protocols designed as scalable in a differentiated manner for each of the system protocol layers are designed to ensure that life critical packets reach their destination as quickly as possible.

The utility of the protocol should remain unchanged regardless of whether it is being executed over several nodes located within the same physical room, or whether the nodes span across the length of an entire city block with nodes appearing and disappearing. Equally important and more so is data sovereignty and security. Given the potential scenarios of a crisis, such as a data wiretap and or the compromise of a single device, it is paramount that high-performance, sensitive configurations, at the very minimum, assign a strong identifier to every packet, encrypt the data to mitigate unauthorized access and validate the contents of every packet for integrity before acceptance.

4.2 Best Practices for Integrating Resilient Protocols into Existing Systems

Incorporating disaster-resilient mobility protocols into a preexisting emergency network requires a detailed actionable framework of a very precise nature regarding effectiveness and interoperability. Prior

to any implementations, a methodical simulation run as a preliminary analysis is conducted to form the core of the actionable framework. Current technology allows the modelling of authentic emergency scenarios during which analytical teams can observe the behavioural response of programmable mobility protocols to various emergency situational variables such as movements and traffic volume, and disconnections to and from the network. Analysts can pre-emptively calibrate and patch the system to mitigate any critical points of failure before the preliminary outages are executed. The principle of modular construction dictates that systems be separated during the loss of emergency mobility protocols within the existing emergency response network. This construction method offers a highly interoperable system which keeps construction economically feasible, reduces over-fitting of critical emergency systems, and pushes vital emergency features to production faster. After cell construction, the system requires refinement through real-world network management data. The system offers parameters such as buffer size, transmission power, and routing thresholds as configurational to the end-user, which is a highly requisite functionality for iterative developmental systems. Automated routing protocols improve system emergency response resiliency. This focus only works with appropriate operator training. Those working in this field should know how the protocol behaves under stress and how to rely on the fail-safes that allow some components to fail without jeopardizing the entire mission.

4.3 Obstacles and Possible Solutions While Carrying Out the Protocol

Implementing adaptive mobility plans is certainly not without its challenges. One of the most significant is that nodes move in ways that are impossible to predict, particularly during emergencies. That uncertainty can sever links and route paths can begin to drift in seconds. Mobility predictions and temporary buffers can help smooth the transitions during short outages, but most low-cost devices cannot support the advanced routing that would really optimize the transitions. Developers can avoid the bottleneck by using thinner, less resource intensive, algorithms that can still accomplish the necessary objectives. It can also be more troublesome when different vendors are using their own proprietary protocols or radio specifications. Custom interfaces and wrapper layers can help bridge those software and hardware integrations, but the real-world environment is still likely to provide a greater challenge than what can be replicated in a controlled lab environment. The best solution is to allow those systems to be active in a sandbox environment where they can continue to be integrated with live feedback data and adaptive loops. Moreover, open ports and weak passwords can provide attackers with a front-row seat and turn thoughtful engineering into a security nightmare. The lightweight encryption of sensitive data, scheduled key rotation, along with node verification, are ways of maintaining trust and keeping data secure in the realm of information technology.

5 Evaluation and Testing

5.1 Evaluating the Protocols for Resilient Mobility Strategy Effectiveness

The deployment of laboratory simulations, field tests, and simulations provides a comprehensive means of assessing protocols under varied conditions. Considering evaluative scope parameters, it is critical to gauge protocols' capabilities to sustain communication with respect to configurations' security, efficiency, and resiliency vis-a vis disrupting the network, mobile nodes, and a minimal resource set. One technique for assessment incorporates network simulation software, particularly NS-3 and OMNeT++. Such applications permit the design of intricate catastrophe patterns while controlling for a host of variables, including mobility patterns, signal jamming, and the nodes' concentration. Emulation platforms assume a distinct role, which is to merge actual field deployment with simulations by employing actual devices, which are interfaced with real and virtual networks, so that the behaviour of protocols can be assessed under authentic ambient conditions. Establishing a required scope for the

performance of simulations and emulations is essential for the areas of testing that demand a measurable degree of precision. Some of the parameters may include:

Packet Delivery Ratio (PDR): Measures how successful the data packet transfer is.

$$PDR = \frac{Number\ of\ Packets\ Received}{Number\ of\ Packets\ sent} \times 100 \quad (4)$$

End-to-End Delay (E2E): Records the mean time taken for a data packet to move from the source to the desired endpoint.

$$E2E\ Delay = \frac{\sum(Arrival\ Time - Send\ Time)}{Total\ packets\ received} \quad (5)$$

Routing Overhead (RO): Shows the additional communications cost as a result of control message traffic.

$$RO = \frac{Number\ of\ control\ packets}{Number\ of\ data\ packets\ delivered} \quad (6)$$

Energy Consumption (EC): Evaluates the average energy spent for each successful transmission.

$$EC = \frac{Total\ energy\ consumed}{Total\ packets\ delivered} \quad (7)$$

These metrics specify the first order of consideration in achieving balance, improving trade-off phenomena, and optimizing efficiency in the protocols.

Figure 3 describes the changes in Packet Delivery Ratio (PDR) of most of the protocols based on the densities of nodes. As the nodes increase in number, specifically from 10 nodes/km² to 50 nodes/km², all of the protocols experienced an increase in PDR which depicts that there is an increase in the network connectivity and enhancement of the routing in denser network. Out of all protocols, Protocol C obtained the highest PDR, probably because of better mobility prediction and efficient use of buffering. Similar PDR was experienced by protocols A and B, but in protocol A it was slightly better because of efficiency in the routing strategies. Protocol B was predicted to have poorer PDR due to its geographical forwarding strategy. This indicates that node density is the primary driver of PDR and indicates that robust protocols are more likely to have improved performance in high density disaster scenarios. The bar graph (Figure 4) illustrates the end-to-end delay experienced by packets, averaged over an increasing number of hops. As predicted, there was an increase in delay for every protocol with the addition of hops. For all levels of hops, Protocol C was superior in that it had the lowest delay, indicating more optimal route selection and less queuing delay per hop.

Protocol A has mid-range performance and Protocol B has performance with the most lag, especially at more than 6 hops. This indicates that Protocol B should not be used in time-critical scenarios. Evidence here confirms that under most circumstances, decreasing the number of hops and/or increasing the efficiency of processing of the intermediate nodes will significantly improve the latency for emergency communication.

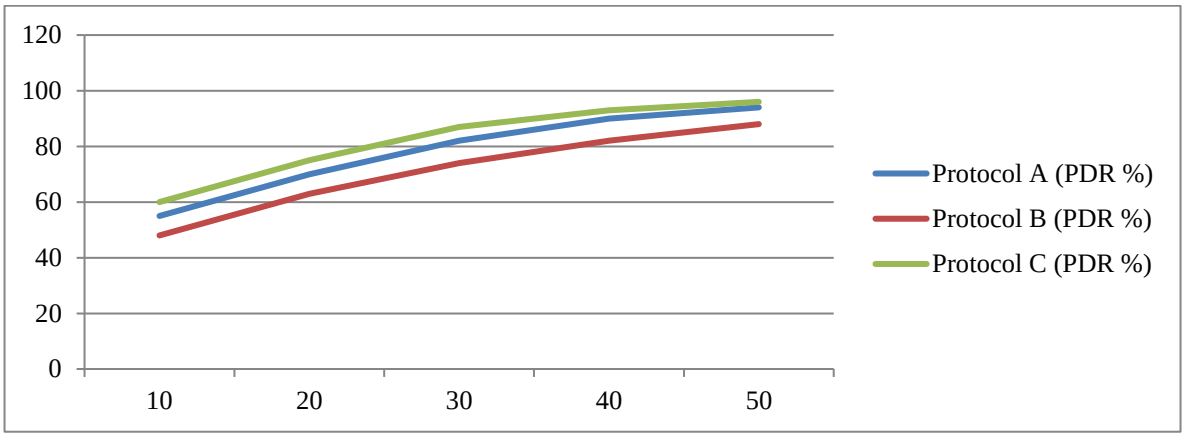

Figure 3: Packet delivery ratio (PDR) vs. node density

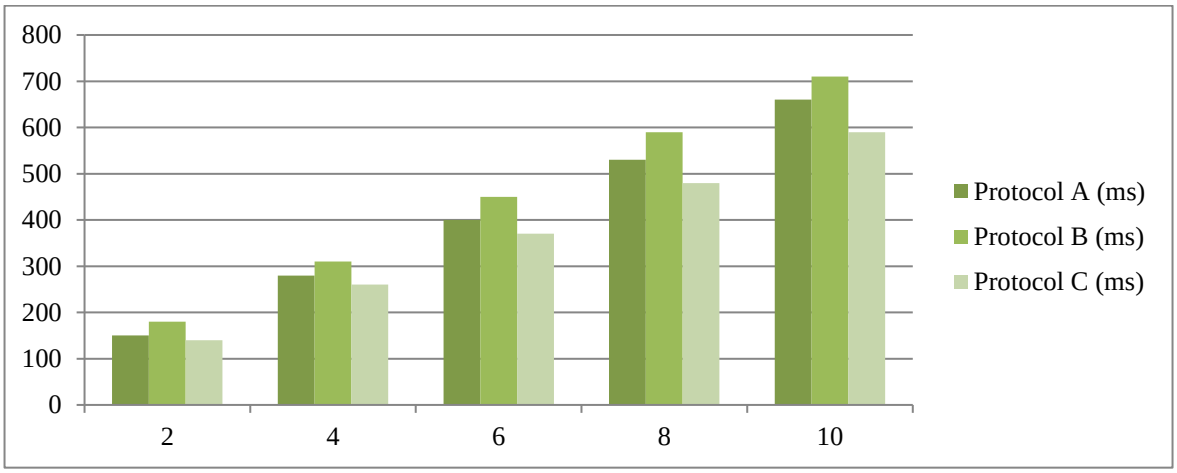

Figure 4: End-to-end delay vs. number of hops

5.2 Case Studies of Testing Resilient Protocols in Disaster Recovery Scenarios

Through simulations, case-based testing helps verify theoretical models. In urban earthquake simulations, resilient mobility protocols were tested in a scenario which involved a high-rise building collapse. Network nodes were placed on drones, command vehicles, and on rescue teams. Packet delivery ratio was proportionately higher with geographic forwarding and mobility prediction compared to standard MANET protocols. In a rural flood response case, protocols were tested in sparse node distribution and intermittent connectivity. Store-and-carry-forward strategies were effective and showed lower packet loss and better energy efficiency, especially with time-tolerant data like environmental readings. Adaptive priority queues and route caching were necessary for real-time communication. Testing also included large-scale forest fire simulations where UAVs acted as relay nodes across dynamic topologies. The results indicated that tactics involving dynamic buffer management combined with delay-aware periodic scheduling achieved the optimal management of message timeliness and reliability.

5.3 Analysis of Findings and Suggestions for Further Investigation

Data gathered from multiple assessments suggested that no one in any of the single protocols outperformed the rest in every location. For example, with the flooding-based protocols, the High Packet Delivery Ratios were achieved at the cost of greater overhead in routing. On the other hand, energy or

delay optimized protocols seem to suffer from higher delivery rates in high mobility scenarios. In order to improve the testing results and direct the protocol developement, multi-metric optimization is suggested to be used in evaluation. One way to do this is to create a performance composite index (CPI) which combines the normalized values of crucial metrics.

$$CPI = w_1 \cdot \frac{PDR}{100} + w_2 \cdot \left(1 - \frac{E2E\ Delay}{Max\ Delay}\right) + w_3 \cdot \left(1 - \frac{EC}{Max\ Energy}\right) \quad (8)$$

Here, w_1, w_2, w_3 are adjustable weights based on application priority. This allows bespoke assessments to be tailored according to distinct disaster recovery objectives. Future testing should integrate realistic mobility models, adversarial scenarios, and human-in-the-loop testing to simulate real-life working environments. Focus on primary sustained deployment efficiency, system extensibility, as well as self-repairing ability of the control protocols will be crucial in the design of reliable systems for disaster recovery.

In Figure 5, we quantify Expl Energy (Cumulative energy expenditure) associated with Ex (data packets) delivered. Selective forwarding (transmission of data to specific nodes), optimized path forwarding) may explain why protocol C (most energy efficient spending) out of all four protocols expended least energy with every data packet. Although protocol A expended more energy (less efficient) than prescribed C, protocol A was still more efficient than protocol B, which seems to be expending energy in-ordinate (more than expected) than wasted transmissions or energy spammed route-inaccessible to fast and efficient transmission protocols. Findings present strong case to prescribing, implementing, and operationalizing energy scoping and contour strategies within designed systems to manage and optimize battery consumption of all designed systems to unstructured, highly fluid domains requiring long-lasting operational endurance (disaster area, etc). Figs 6 present each protocol (per each designed network) Routing Overhead (RO) quantified and graphed to depict impact of increasing network size designed to operate within 25 to 125 nodes. Fig 6 confirms protocol B Had Highest Overhead. Therefore, it controls more packets than other cohorts theoretically increased network inefficiencies, more than other protocols. C is best placed, lowest overhead and balanced, reducing control overhead. Thus, control communications were streamlined. To be less elaborate, protocol is placed average control to adapt efficient dynamic routing with beacons. Informing us that lower overhead also increases protocol scalability and makes Protocol C more appropriate for large-scale disaster communication deployments (Figure 6).

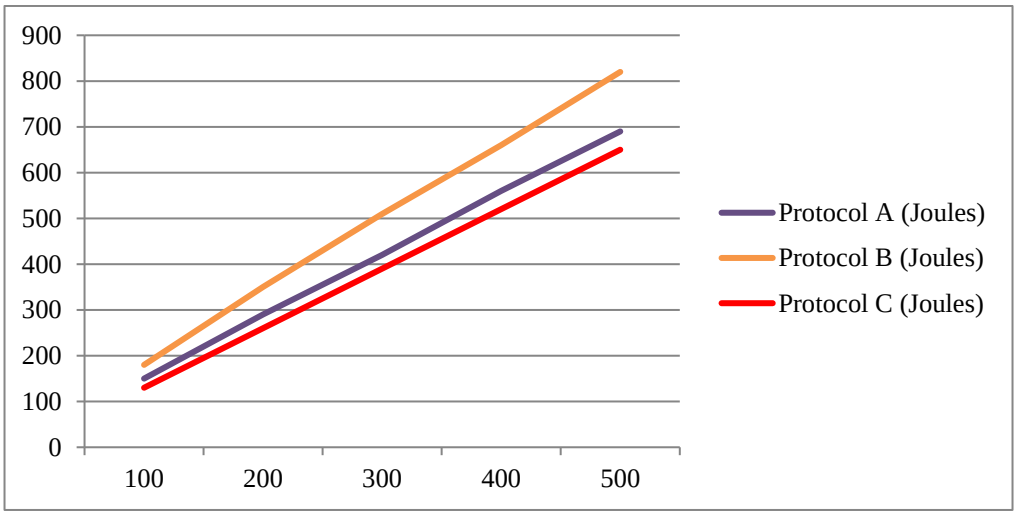

Figure 5: Energy consumption vs. data packets delivered

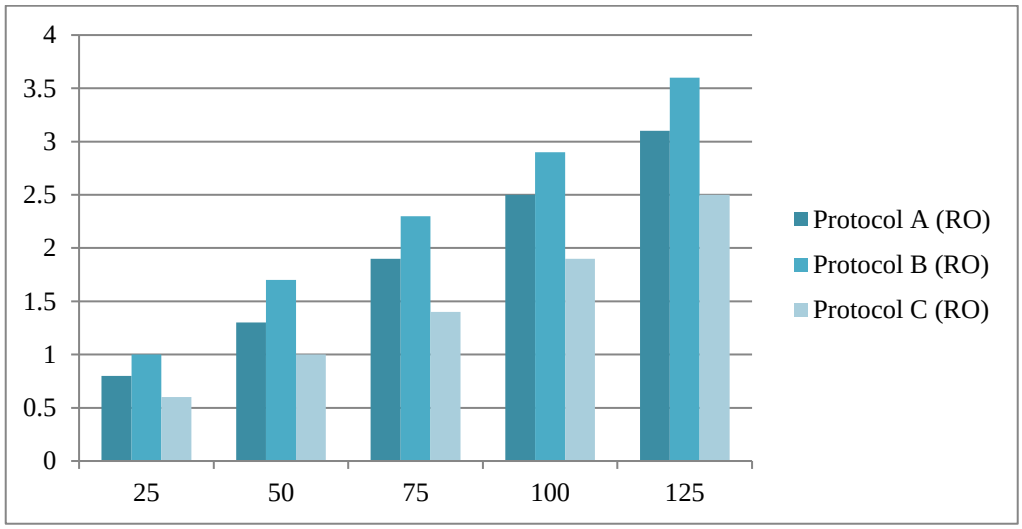

Figure 6: Routing overhead vs. network size

5.4 Comparison of Protocol Performance Across Essential Metrics:

Figure 7 provides details for comparing four types of protocols, Epidemic Routing, Spray and Wait, MaxProp, and Geo-Routing, in terms of three criteria: Packet Delivery Ratio (PDR), Energy Consumption, and End-to-End Delay (E2E).

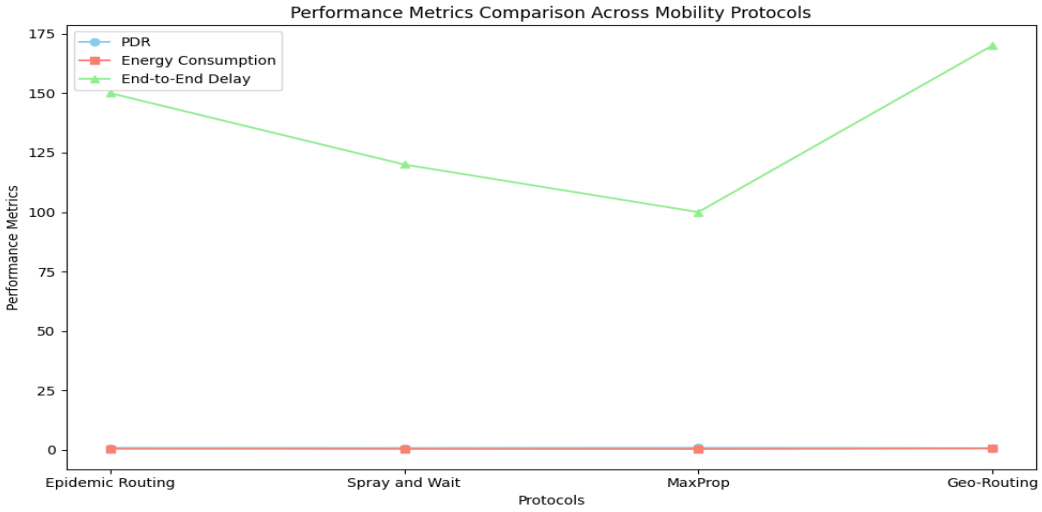

Figure 7: Performance metrics comparison across mobility protocols

The plot shows how each mobility protocol performs in regard to the Packet Delivery Ratio (PDR), the energy consumption, and the end-to-end (E2E) delay. Blue indicates PDR, which measures the success in delivering packets for each of the protocols, and red represents energy consumption, which indicates how much energy was used to transfer the data. Green represents the end-to-end delay, which measures the delay in milliseconds with which the data packets travel from the origin to the destination. Geo-routing shows the most concerning issue of delay, i.e. it takes a significantly longer time to deliver packets than the other protocols do. On the other end of the spectrum, Epidemic Routing and Spray and Wait protocols are less concerning energy consumption wise, evidenced by their low energy consumption levels. Likewise, MaxProp shows a higher PDR than the others, and thus shows a more desirable protocol in the PDR trade-off scenario. Such analysis is vital for the decision-makers to know

trade-offs in the protocols to enable a choice of most relevant protocol based on disaster recovery priorities e.g. energy, speed of communication, or delivery.

6 Conclusion

The study highlighted in this paper emphasizes the importance of resilient mobility protocols in improving the reliability and efficiency of communication systems used in disaster recovery. The study shows that traditional mobility solutions are in most cases inadequate because they do not work under extreme conditions that are common during and after a disaster. Via using the resilient mobility framework proposed in the paper in addition to the results of simulations alongside performance metrics concerning packet delivery ratio, end to end delay, energy efficiency, and routing overhead improvements in connectivity and cost reduction of delay and resources were achieved. The examined scenarios of scarce networks, movement of nodes, and intermittent connectivity respectively, were able to protocol throughput. These findings can support strategic emergency response planning in the design of adaptive and survivable networks of communication to function in extreme adaptability. The study also suggests the AI prediction of mobility, cross layer optimization, and the addition of layer security to mobility protocols to be of interest for further robustness. Field trial and real-time adaptability recommendations were also made to move the theoretical models towards actual implementation. Disaster recovery processes see seamless mobility protocols as essential not only as seamless interfaces but also as core elements for the effectiveness of communication systems.

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