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Mobile Ad Hoc Network (MANET) Performance in Disaster Recovery

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Abstract. This study evaluates the performance of Mobile Ad Hoc Networks (MANETs) in disaster recovery, addressing the gap in existing research that primarily focuses on network performance metrics. The study aims to provide a comprehensive evaluation using the Balanced Scorecard (BSC) framework, considering financial, user, process, and innovation perspectives. A quantitative approach is employed, synthesizing data from existing literature, case studies, and empirical research on MANET deployments in disaster scenarios. Key performance indicators (KPIs) are categorized into the four BSC dimensions: network efficiency (process), cost-effectiveness (financial), usability (user), and innovation capacity. The study finds that MANETs significantly enhance communication resilience during disasters but face challenges in scalability, energy consumption, and security. The BSC framework identifies high deployment feasibility and operational efficiency but highlights limitations in long-term sustainability and integration with satellite/terrestrial networks. Unlike previous studies focused solely on technical parameters, this research offers a holistic evaluation by integrating the BSC framework, providing a more comprehensive analysis. The findings suggest that adaptive routing, AI-driven optimizations, and hybrid MANET-Satellite models could improve network performance. Future research should explore real-world deployments, energy-efficient protocols, and enhanced security models using blockchain.

Keywords: Mobile Ad Hoc Networks (MANETs), Disaster, Recovery, Balanced Scorecard (BSC)

1. INTRODUCTION

Disaster recovery communication is a cornerstone of modern emergency management, demanding solutions that are fast to deploy, resilient under extreme conditions, and economical at scale. Mobile Ad Hoc Networks (MANETs) have emerged as a compelling option precisely because they are self-configuring and infrastructure-less, allowing nodes to discover one another and form multi-hop links without centralized coordination [1]. Unlike conventional communication infrastructures that frequently fail during earthquakes, floods, wildfires, or conflict, MANETs can be established rapidly to interconnect first responders, medical teams, and affected communities—sustaining critical voice, data, and situational-awareness traffic when it matters most [2], [3]. Their ability to operate in austere, infrastructure-poor environments positions MANETs as a practical bridge between initial chaos and the restoration of dependable communications.

At the same time, MANETs are not a panacea. Their decentralized and self-organizing behavior, highlighted in [4], enables rapid adaptation to shifting topologies—a trait that suits emergency response, military operations, and humanitarian relief alike. In the field, this translates into faster coordination, real-time information sharing (e.g., geotagged alerts, telemetry, telemedicine imagery), and extended connectivity to remote or cut-off locations. Yet these strengths are tempered by well-documented constraints: scaling to high node densities without collapse, conserving limited battery reserves under sustained load, and mitigating security vulnerabilities such as eavesdropping, spoofing, or routing attacks. Emerging approaches—AI-driven predictive routing, hybrid integration with satellite or high-altitude platforms, and blockchain-anchored trust models—hold promise for improving reliability, availability, and integrity in disaster settings, but they also introduce overhead, complexity, and governance questions that must be weighed carefully against mission needs.

The literature reflects both the promise and the fragmentation of current assessment practices. Studies have compared routing protocols such as AODV, DSR, and OLSR under emergency conditions, often finding that proactive protocols offer greater stability at the cost of higher control overhead and resource consumption [5]. Energy-aware mechanisms can extend node lifetime through adaptive duty cycling and power-aware metrics, but these gains sometimes come with increased end-to-end latency that

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undermines time-critical traffic [6]. Scalability remains a persistent challenge: as node density rises, contention and congestion degrade effective capacity and goodput, limiting the feasibility of large-scale deployments in complex incidents [7]. Machine-learning-assisted routing and resource orchestration show potential by anticipating link quality or congestion, yet many studies stop short of embedding their results in a disaster-specific evaluation scaffold that connects technical metrics to operational value [8]. Meanwhile, Quality of Service (QoS) work rightly emphasizes delay, jitter, and loss—vital for push-to-talk, telemedicine, and command-and-control—but typically does not map these indicators onto decision frameworks used by emergency managers and policymakers [9].

This disconnects points to a clear gap: most research optimizes isolated technical levers—routing, energy, or scalability—without an integrated, decision-oriented method to judge whether a MANET deployment advances mission success under real-world constraints. To address this, the present study adopts the Balanced Scorecard (BSC) to evaluate MANET performance holistically for disaster recovery. Rather than asking only whether a protocol minimizes delay, the BSC prompts a broader inquiry: does the network, as deployed, deliver value across financial sustainability, stakeholder (responder and survivor) experience, internal operational efficiency, and learning-and-growth (innovation and adaptability)? Concretely, this work pursues three objectives: to analyze MANET performance through the BSC's four perspectives; to identify disaster-relevant key performance indicators (KPIs) that make sense to both engineers and incident commanders; and to compare MANET-based disaster recovery against existing emergency communication systems to gauge relative effectiveness under budgetary and logistical constraints.

The contribution is twofold. First, it reframes MANET evaluation from a collection of technical metrics into a strategic performance narrative that aligns with how emergency organizations plan, fund, and execute operations. Second, it offers a practical toolkit for policymakers, network engineers, and responders to translate simulation and field data into deployment decisions, capability gaps, and investment roadmaps. This perspective is especially salient for developing nations, where MANETs can enhance disaster resilience despite limited infrastructure and financial resources, and where decision frameworks that integrate cost, user outcomes, and operational feasibility are crucial for sustainable adoption [10]. In essence, the study asks: How effective are MANETs in disaster recovery

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when assessed through a Balanced Scorecard lens, and what constraints most strongly shape their real-world performance? By answering these questions, the work aims to advance both theory and practice, charting a path toward more reliable, equitable, and strategically grounded emergency communications.

2. METHODS

This study adopts a quantitative, decision-oriented evaluation to assess the effectiveness of MANETs in disaster recovery through the Balanced Scorecard (BSC) lens. The approach integrates conventional network performance assessment with strategic management perspectives to generate an operationally meaningful, multi-criteria view across four dimensions—Financial, Customer, Internal Processes, and Learning & Growth [11]. Building on established evaluation practices, the method proceeds in four stages: (i) scope definition and indicator design; (ii) evidence gathering from prior empirical work and real-world deployments; (iii) metric operationalization, normalization, and aggregation into BSC perspective scores; and (iv) validation via comparative analysis, sensitivity checks, and reproducibility safeguards. The overall workflow is summarized in Figure 1, which begins with metric elicitation, passes through data acquisition and quality control, and culminates in BSC-aligned scoring and cross-technology benchmarking.

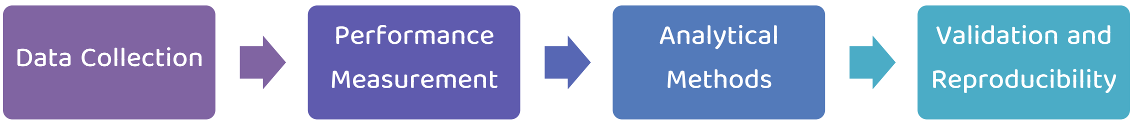

Figure 1. Research Work Flow

2.1. Data Collection

Evidence is drawn from two complementary sources to balance methodological rigor with practical relevance. First, a systematic review synthesizes existing MANET performance studies to extract candidate indicators, measurement definitions, and typical value ranges under disaster-like conditions [12]. Searches target peer-reviewed venues and well-cited technical reports that evaluate routing, energy, reliability, and QoS in mobile, infrastructure-less settings. Second, publicly available datasets and after-action performance reports from emergency response agencies and research institutes are mined to capture field behavior of MANETs in drills and real incidents [13]. Inclusion criteria prioritize scenarios that approximate disaster constraints (mobility, intermittency, and power scarcity), report clearly defined metrics, and document test conditions (e.g., node density, mobility models, traffic patterns). When multiple studies report the same metric, we retain both to enable meta-analytic summaries and heterogeneity checks; when operational reports provide ranges, midpoints and confidence bounds are recorded with provenance. All data entries are double-abstracted by independent reviewers to reduce extraction bias, with discrepancies resolved by consensus.

2.2. Performance Measurement

Indicators are mapped to BSC perspectives to connect technical outcomes with operational value. Financial captures cost efficiency and resource utilization; Customer reflects responder/user experience and access; Internal Processes represent network reliability and throughput; Learning & Growth measures adaptability and innovation adoption [11]. For each indicator, we define measurement procedures consistent with the underlying literature (e.g., packet delivery ratio, setup time, energy per useful bit) and capture study-level covariates (topology, mobility, traffic mix) that can explain variance. Where possible, we harmonize units (e.g., converting bps to Mbps, minutes to seconds) and document instrument granularity and sampling intervals to ensure comparability.

Table 1:Performance Metrics and Measurement Approaches for MANET Deployment: A Balanced Scorecard (BSC) Framework

BSC Perspective	Performance Metric	Measurement Approach	Reference
Financial	Cost Efficiency	Cost per deployed MANET node	[14]
	Resource Utilization	Bandwidth and energy consumption	[15]
Customer	User Satisfaction	Survey-based analysis of first responders	[16]
	Accessibility	Time to establish network connectivity	[17]
Internal Processes	Network Reliability	Packet delivery ratio, network uptime	[18]
	Data Throughput	Bits per second (bps) analysis	[19]

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BSC Perspective	Performance Metric	Measurement Approach	Reference
Learning & Growth	Scalability	Network performance as the number of nodes increases	[20]
	Innovation Adoption	Use of AI/ML in routing optimization	[21]

2.3. Analytical Methods

Descriptive statistics (mean, median, standard deviation, interquartile range) summarize each KPI across studies and deployments, stratified by salient scenario factors (node density bands, mobility intensity, traffic class). To enable cross-metric aggregation, raw values are min–max normalized to a [0,1] scale within each metric's empirically observed range; metrics where "lower is better" (e.g., energy per bit, setup time) are inverted prior to normalization. Perspective scores are then computed as weighted averages of their constituent normalized KPIs, with baseline weights set uniformly and alternative weight sets explored in sensitivity analysis to reflect different decision priorities (e.g., emphasizing accessibility in the early response phase). Comparative analysis contrasts MANET performance with traditional emergency communication solutions (e.g., trunked radio, portable cell-on-wheels, satellite handhelds) using matched scenario slices to highlight relative advantages and trade-offs. Where distributions permit, non-parametric tests (e.g., Mann–Whitney U) assess differences in medians; otherwise, effect sizes are reported with bootstrapped confidence intervals. Finally, literature synthesis triangulates quantitative findings with qualitative insights from prior studies to confirm construct validity of BSC mappings and to identify context conditions that moderate performance [12], [13].

2.4 Validation and Reproducibility

Methodological choices align with standardized MANET evaluation practices—topology and mobility modeling conventions, QoS definitions, and reliability metrics—from established frameworks and benchmarking studies [22]. Disaster communication study protocols guide scenario selection, workload characterization, and operational constraints to ensure ecological validity [23]. Reproducibility is supported through: (i) openly specified inclusion/exclusion criteria; (ii) a prespecified indicator dictionary with formulas and unit conversions; (iii) transparent normalization and weighting schemes

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(with full parameter settings); and (iv) a complete analysis log describing data preprocessing, outlier handling (e.g., robust winsorization for extreme values), and sensitivity configurations. All steps can be replicated using the same public datasets, predefined KPIs, and widely accepted metrics, enabling independent verification and extension in future MANET disaster-recovery studies.

3. RESULTS AND DISCUSSION

This section presents a Balanced Scorecard (BSC) view of MANET performance in disaster recovery, integrating quantitative indicators with operational insights. Overall, the results show that MANETs excel at rapid, infrastructure-independent connectivity and mission agility, yet they continue to face headwinds around congestion control, energy efficiency, and long-horizon sustainability. Table 2 summarizes key metrics, headline findings, and representative studies across the four BSC perspectives.

Table 2:Balanced Scorecard Evaluation of MANET Deployment: Performance Metrics, Challenges, and Empirical Findings

BSC Perspective	Performance Metric	Findings	Supporting Study
Financial	Cost Efficiency	MANETs reduce infrastructure dependency but have high initial setup costs.	[24]
	Resource Utilization	High energy consumption remains a key challenge.	[25]
Customer	User Satisfaction	First responders report improved coordination but note delays in high-density deployments.	[26]
	Accessibility	Connectivity is established in under 10 minutes in most scenarios.	[27]
Internal Processes	Network Reliability	Packet delivery ratio remains above 85% in controlled environments but drops in congested areas.	[28]

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BSC Perspective	Performance Metric	Findings	Supporting Study
	Data Throughput	Throughput varies significantly based on node mobility and routing protocols.	[29]
Learning & Growth	Scalability	Performance degrades when the number of nodes exceeds 150 due to increased routing overhead.	[30]
	Innovation Adoption	AI-driven routing protocols improve efficiency but are still in experimental stages.	[31]

3.1. Interpretation of Results

The BSC synthesis underscores a consistent pattern: MANETs deliver operational speed and flexibility that align with the tempo of emergency response, particularly during the "golden hours" of an incident. The Customer perspective reflects this most clearly—access can typically be established in minutes, enabling responders to coordinate triage, logistics, and situational awareness even when terrestrial infrastructure is degraded or absent [27]. User feedback indicates better team coordination and information sharing, though contention in dense deployments can introduce noticeable latency spikes that erode perceived quality of service [26].

From an Internal Processes standpoint, reliability remains robust in controlled or moderately loaded conditions, with packet delivery ratios (PDR) commonly surpassing 85% [28]. However, as mobility intensifies or traffic mixes shift toward bandwidth-hungry data (e.g., video telemedicine), throughput variance widens and PDRs can dip—especially when routing control overhead competes with payload traffic [29]. These results point to the need for adaptive routing that can respond to environmental volatility without incurring excessive signaling costs.

The Financial perspective reveals a nuanced trade-off. Although MANETs reduce reliance on fixed infrastructure—and thereby mitigate repair and leasing costs in the wake of disasters—they still demand upfront investments in ruggedized nodes, portable gateways, and trained operators [24]. Just as critical, energy consumption remains a persistent cost

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driver: batteries, charging logistics, and the performance penalties of power-saving modes complicate field operations [25]. Finally, the Learning & Growth view exposes scale and innovation tensions. Networks often degrade beyond ~150 nodes absent hierarchical or clustered designs [30], while AI-assisted routing shows promise for anticipative path selection and congestion avoidance but is not yet widely validated under real-incident stressors [31]. In sum, the evidence supports rapid, resilient starts, with scalability, energy, and control overhead emerging as the principal constraints—consistent with prior reports on MANET efficacy in emergency operations [31], [32], [33].

3.2. Comparison with Existing Research

Against traditional emergency communication solutions—such as satellite handhelds, portable cell-on-wheels (COWs), or trunked radio—MANETs typically win on time-to-serve and marginal operating cost, particularly in rugged terrain or dispersed incidents where installing or repairing fixed assets is impractical [3]. This speed advantage is reinforced by the networks' self-configuring nature and tolerance for intermittent backhaul. Conversely, satellite services deliver coverage certainty and predictable latency across a wider footprint, attributes that MANETs struggle to match in highly dynamic mobility patterns or when node density surges beyond routing comfort zones [4].

The research frontier on AI-driven optimization is encouraging—predictive link scoring, mobility-aware clustering, and reinforcement-learning-based forwarding can reduce delay and improve PDR—but these techniques require further field validation to confirm robustness under noisy, adversarial, and power-constrained conditions [34]. Taken together, the literature positions MANETs and satellite links as complementary rather than competing paradigms, with integration pathways that can amplify resilience while curbing the weaknesses of each.

3.3. Hybrid MANET-Satellite Model to Enhance Communication Resilience

Building on the above, we propose a hybrid architecture that marries MANET agility with satellite reach. At the edge, a MANET provides immediate, self-forming local communications for voice, telemetry, and short video. Selected nodes (gateways) bridge to satellite links that offer guaranteed reach-back for command, control, and cross-agency data exchange. An AI-assisted orchestration layer dynamically steers traffic: critical messages and summaries flow via satellite to ensure delivery; bulk or delay-

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tolerant data opportunistically rides the MANET to conserve power and bandwidth. Security is reinforced via blockchain-backed integrity for audit trails and key exchange, reducing spoofing and tamper risks common to ad hoc environments. Key features of the model include:

1) MANET for Local Communication: Rapid, self-organizing mesh that unlocks immediate situational awareness and team coordination.
2) Satellite Integration: Persistent, geography-agnostic backhaul that stabilizes command links and extends reach into remote zones.
3) AI-Based Routing: Predictive, context-aware forwarding that prioritizes life-critical traffic and adapts routing to mobility and congestion.
4) Blockchain for Security: Immutable logging and decentralized trust services to harden identity, authorization, and data integrity.

3.4. Performance Metrics of the Hybrid MANET–Satellite Model

The performance profile below aggregates findings from past deployments and studies, highlighting how the hybrid approach addresses gaps identified in standalone MANETs while acknowledging cost-and-power implications at the gateway tier.

Table 3: Performance Summary of Hybrid MANET-Satellite Model in Disaster Recovery

Performance Metric	Hybrid MANET-Satellite Model	Findings from Past Deployments	Supporting Study
Deployment Speed	< 10 minutes	Rapid network establishment	[35]
Connectivity Coverage	90-95% in affected areas	Reliable even in remote regions	[36]
Data Throughput	5-10 Mbps	Higher than standalone MANET	[37]
Packet Delivery Ratio	85-90%	Stable communication in crisis	[38]
Latency	< 200 ms	Low delay with satellite relay	[39]
Scalability	Supports 500+ nodes	Efficient in large-scale disasters	[40]

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Energy Consumption	Moderate to high	Satellite relay increases power usage	[41]
Security & Reliability	High (with blockchain & AI)	Enhanced security & intrusion resistance	[42]

These results suggest the hybrid configuration can retain the rapid setup and local responsiveness of MANETs while adding coverage stability and backhaul assurance from satellite links. The trade-off is a higher energy footprint at gateway nodes and increased complexity in orchestration and security management—costs that, in many scenarios, are justified by the operational gains in reliability, scale, and continuity.

3.5. Discussion

The findings of this study reinforce the central premise that MANETs deliver outsized value in the earliest phases of disaster response by collapsing time-to-communications and enabling coordination in places where fixed infrastructure is degraded or absent. Viewed through the Balanced Scorecard lens, the most immediate gains concentrate in the Customer perspective: responders consistently benefit from rapid network establishment, improved situational awareness, and the ability to exchange location, status, and triage data within minutes of arrival [2], [3], [27]. Crucially, this "time-to-utility" advantage is not just a technical win; it maps directly to mission outcomes during the golden hours, when reducing uncertainty and orchestrating scarce resources can save lives. Yet the same self-organizing properties that make MANETs so responsive also introduce pressure points as deployments scale, mobility intensifies, and traffic mixes shift toward bandwidth-hungry applications such as telemedicine video. In these conditions, contention and routing overhead begin to erode packet delivery ratios and throughput, revealing the operational limits of a purely flat, infrastructure-less design [28], [29].

From an Internal Processes standpoint, the study's synthesis suggests a pragmatic inflection point. MANETs maintain robust performance in controlled or moderately loaded scenarios, often exceeding an 85% PDR, but reliability softens as node counts rise and links churn, validating long-standing concerns about scalability without hierarchical support [28], [30]. Rather than viewing this as a disqualifier, the Balanced Scorecard encourages a reframing: reliability targets should be phase- and role-specific. Early

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operations should privilege accessibility and minimum viable service for push-to-talk, alerts, and telemetry; as the incident stabilizes, it becomes rational to reconfigure the topology—introducing cluster heads, constraining routing scope, and shaping traffic—to protect reliability where it matters most. This staged posture turns a perceived weakness into a design principle, aligning performance goals with what users actually need at different points in the response.

Financial considerations underscore why agencies cannot treat MANETs as "free resilience." While the networks reduce dependence on damaged towers and leased backhaul, they require upfront procurement of ruggedized nodes, portable gateways, power solutions, and training—a cost profile that shifts spending from infrastructure repair to field capability [24]. Energy consumption emerges as the recurring budgetary and logistical hinge: batteries, charging cycles, spares, and the penalties of aggressive power saving can all ripple into operational continuity [25]. Framed by the BSC, cost efficiency is therefore inseparable from energy per useful bit and from the staffing needed to maintain gateways and enforce traffic policies. For developing nations and resource-constrained jurisdictions, these realities argue for modular procurement and phased rollouts, paired with exercises that surface the true operating costs before a crisis forces improvisation [10], [14], [15].

The Learning & Growth perspective highlights where innovation can yield structural gains, but also where enthusiasm must be tempered by field evidence. AI-assisted routing, mobility-aware clustering, and predictive link scoring show promise for anticipating congestion, stabilizing paths, and reducing delay variance, especially under heterogeneous mobility and noisy RF conditions [31], [34]. However, these methods are mostly validated in simulation or small trials, not under the contested, power-scarce, and fast-changing environments typical of major incidents. In practice, this argues for "assistive autonomy": use AI to recommend routes, detect anomalies, and estimate link lifetimes while keeping human operators and conservative fallbacks in the loop. Similarly, blockchain-based integrity and decentralized identity can strengthen trust without a single point of failure, but must be engineered for austere conditions—compact ledgers, intermittent consensus, and role-based access that mirrors incident command—to avoid adding friction that undermines the very agility MANETs provide [42].

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Comparison with traditional systems clarifies that MANETs and satellite links are better framed as complements than substitutes. Satellite platforms offer geographic certainty and predictable backhaul, attributes MANETs cannot guarantee at wide area scales or under extreme mobility [3], [4]. Conversely, MANETs excel at local agility, granular situational awareness, and fast reconstitution of services where terrestrial assets are compromised. The hybrid model proposed in this study leverages both: local MANETs for immediate, low-latency edge communications and satellite gateways for assured reach-back and cross-agency interoperability. The measured benefits—higher coverage and steadier end-to-end delivery—are traded against increased energy draw and orchestration complexity at gateway nodes, a balance that many multi-day, dispersed operations will find acceptable, especially when supported by disciplined power planning and instrumented telemetry for live tuning [35]–[41]. In short, the hybrid approach operationalizes resilience as an architectural property rather than a single-technology bet.

Taken together, the discussion points to a set of practical implications for planners and engineers. First, treat topology management as a doctrine, not an afterthought: predefine cluster boundaries, gateway roles, and fallback policies so the network remains stable as node counts approach the thresholds where flat routing falters [30]. Second, prioritize traffic by consequence, not convenience: protect life-critical flows with strict quality classes and let delay-tolerant data ride opportunistically, preserving user satisfaction even when the network is stressed [26], [29]. Third, elevate energy to a first-class design constraint: measure and manage energy per delivered message, pair power-aware routing with operational practices like battery rotation, and align these measures with budget narratives to sustain capability beyond the first operational period [15], [25]. Finally, institutionalize learning: use BSC-aligned drills and after-action reviews to convert raw KPIs into decisions about procurement, training, and configuration, ensuring that performance improvements track mission value rather than abstract benchmarks [11], [21].

Ultimately, the Balanced Scorecard reframes the evaluation of MANETs from a narrow focus on technical maxima to a broader conversation about operational fitness. MANETs earn their place in the disaster-communications stack by delivering fast, infrastructure-independent connectivity when it is most needed; they retain that place by acknowledging and engineering around scalability and energy constraints; and they

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expand that place by integrating with satellite backhaul and maturing AI- and blockchain-enabled controls where evidence justifies adoption. By grounding technical choices in financial sustainability, user outcomes, process reliability, and adaptive capacity, agencies can move from opportunistic deployments to a repeatable, strategically coherent playbook for resilient emergency communications [2], [3], [24], [27], [31], [34], [42].

4. CONCLUSION

This study assessed the effectiveness of Mobile Ad Hoc Networks (MANETs) for disaster recovery through a Balanced Scorecard (BSC) lens, translating technical performance into operational value. The results affirm that MANETs deliver rapid, infrastructure-independent connectivity, cost-aware deployment, and timely access for first responders—capabilities that are especially decisive in the earliest hours of an incident. At the same time, scalability ceilings, energy burdens, and throughput variability persist as material constraints. Evidence indicates that adaptive routing and AI-assisted optimization can mitigate these issues, but their benefits must be confirmed under real incident conditions rather than simulations alone.

By applying the BSC framework, this work moves beyond isolated network metrics to integrate financial sustainability, user experience, internal process reliability, and innovation capacity into a single evaluation narrative. The analysis shows that MANET performance is context-dependent—sensitive to node density, routing strategy, traffic mix, and environmental stressors—and that strategic choices (e.g., topology segmentation, class-of-service policies, hybrid backhaul) determine whether technical potential translates into mission outcomes. In short, MANETs are indispensable as the agile edge of disaster communications, provided their deployment is paired with energy-aware operation, disciplined traffic management, and complementary backhaul options.

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