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A Realistic Hybrid Mobility Model for Search-and-Rescue Teams in Mobile Ad Hoc Networks

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ABSTRACT

Mobile Ad Hoc Networks (MANETs) play a vital role in emergency communication, particularly when conventional infrastructure is damaged or inaccessible during large-scale disasters. Their capacity to self-organise and operate without fixed support makes them indispensable in Search-and-Rescue (SAR) operations, where rapid coordination and reliable information exchange can determine survival outcomes. The effectiveness of any MANET deployment, however, depends heavily on the accuracy of the mobility model used to simulate node movement. Existing approaches, including entity-based and group-based models, have provided valuable insights into network behaviour but remain limited in their ability to capture the complex, coordinated, and constantly evolving movement patterns that characterise SAR environments.

This conceptual paper develops a theoretical foundation for a hybrid mobility model that integrates essential features from both paradigms. Drawing on established MANET literature and lessons from real disaster scenarios, the paper argues that SAR mobility reflects both individual autonomy and collective coordination, making a composite model necessary. The proposed framework embeds role differentiation, dynamic switching between entity and group behaviours, scenario-driven spatial constraints, and flexible cohesion thresholds. Together, these features offer a more holistic representation of SAR mobility and provide a realistic basis for evaluating MANET performance under disaster conditions.

The discussion highlights key gaps in existing models, conceptualises the structural features of a hybrid approach, and outlines its potential contributions to simulation realism, routing protocol evaluation, and emergency communication planning. The paper concludes by identifying methodological considerations and future research opportunities for refining hybrid mobility modelling within disaster-response wireless networks.

KEYWORDS

Mobile Ad Hoc Networks, mobility modelling, hybrid mobility model, search-and-rescue, disaster response, routing protocols, simulation, wireless communication.

INTRODUCTION

Communication failures remain among the most pressing challenges during large-scale disasters. Earthquakes, hurricanes, wildfires, and terrorist incidents frequently damage or destroy conventional communication infrastructure, leaving emergency responders dependent on decentralised systems. Mobile Ad Hoc Networks (MANETs) have emerged as a promising solution because they allow nodes to self-organise and function without fixed infrastructure, enabling rapid deployment in unpredictable environments (Younis et al., 2021). Their adaptability makes them particularly valuable in Search-and-Rescue (SAR) operations, where coordination and information exchange can determine survival outcomes (Goncalves et al., 2020).

The performance of MANETs is shaped by the mobility models used in simulation. These models define how nodes move, interact, and sustain communication, directly influencing outcomes such as connectivity, packet delivery, link stability, and routing efficiency (Pullin et al., 2018). Entity-based models capture the behaviour of individual nodes, while group-based models reflect coordinated collective movement. Each approach offers strengths, yet neither fully captures the dynamic and layered mobility patterns observed in SAR contexts. Teams must disperse and regroup, adapt to unpredictable terrain, and balance collective coordination with individual autonomy (Bodra & Amritanjali, 2019). Recent studies emphasise that unrealistic mobility assumptions can lead to misleading performance evaluations, underscoring the need for models that reflect operational realities (Sahu & Mishra, 2024).

Hybrid mobility models have been proposed as a way to integrate the strengths of both entity-based and group-based approaches. Analytical and simulation studies demonstrate that hybrid models can better represent the multi-level movement patterns characteristic of SAR teams, where individuals act autonomously but remain tethered to group objectives (Wu et al., 2008; Mnati et al., 2024). Emerging research highlights the importance of incorporating environmental constraints, terrain unpredictability, and task-driven dispersal into mobility modelling to improve the realism of MANET simulations (Muthukumar & Nagarajan, 2025). Such hybrid approaches not only enhance the accuracy of performance evaluation but also provide insights for designing communication strategies that are resilient under disaster conditions.

This paper develops the conceptual foundation for a hybrid mobility model tailored to SAR teams operating in disaster environments. The argument advanced here is that a hybrid approach is essential to represent the multi-level movement patterns characteristic of real-world emergency response. The discussion begins with the theoretical underpinnings of mobility modelling, highlights the limitations of existing approaches, outlines the proposed hybrid structure, and considers its potential contributions to MANET research and disaster-response communication strategies. Situating the model within recent advances in MANET design and SAR communication planning, the paper aims to contribute to both theoretical development and practical application in disaster management.

THEORETICAL BACKGROUND

Mobility models function as behavioural templates for simulating node movement in Mobile Ad Hoc Network (MANET) environments. They determine how simulation data approximates real-world behaviour and therefore influence the reliability of performance evaluations. The accuracy of these models is critical, as unrealistic assumptions can distort outcomes related to connectivity, routing efficiency, and resilience under disaster conditions (Pullin et al., 2018). In the context of Search-and-Rescue (SAR) operations, where communication reliability directly affects life-saving coordination, mobility modelling becomes more than a technical exercise; it is a foundation for operational planning.

Entity-based mobility models, such as the Random Waypoint, Random Walk, and Gauss–Markov models, treat each node as independent. These models are characterised by stochastic changes in speed, direction, and pause times, which allow them to simulate unpredictable or free-form movement patterns (Bai & Helmy, 2009). Their strength lies in representing environments where individuals move autonomously, such as pedestrian traffic or crowd dispersal. However, their limitations become evident in SAR missions, where responders rarely act in isolation. The oversimplification of structured teamwork reduces the realism of simulations and can misrepresent network performance in coordinated emergency contexts (Sahu & Mishra, 2024).

Group-based models, such as the Reference Point Group Mobility Model (RPGM), capture coordinated movement by treating nodes as members of a logical group with a shared centre and motion vector (Bonuccelli, Martelli, & Pelagatti, 2004). These models are better suited to scenarios where teams move collectively, such as military platoons or classroom groups. They assume a relatively high degree of synchronisation between nodes, which contradicts actual SAR behaviour. In practice, responders often diverge from team movements to perform localised tasks, investigate structural hazards, or attend to victims. Recent studies confirm that strict synchronisation assumptions fail to capture the fluidity of SAR operations, where autonomy and coordination coexist (Bodra & Amritanjali, 2019).

Disaster scenarios further complicate mobility patterns due to geographical obstacles, debris, hazardous zones, and continuously shifting operational objectives. Terrain irregularities, collapsed infrastructure, and environmental hazards introduce constraints that neither entity-based nor group-based models adequately capture. Research emphasises that real-world SAR operations involve fragments of both individual and coordinated movement, making neither model type independently sufficient (Goncalves et al., 2020; Kumar et al., 2024). Hybridised perspectives have therefore gained traction, integrating structural cohesion with individual autonomy to reflect the fluctuating spatial and operational demands of disaster environments (Mnati et al., 2024).

Hybrid mobility models combine the stochastic flexibility of entity-based approaches with the structural logic of group-based models. They allow for dispersal and regrouping, task-driven divergence, and adaptive coordination, all of which are central to SAR missions. Emerging research highlights the importance of incorporating environmental constraints, terrain unpredictability, and mission-driven dispersal into mobility modelling to improve the realism of MANET simulations (Muthukumar & Nagarajan, 2025). Embedding these features, hybrid models not only enhance simulation fidelity but also provide actionable insights for designing communication strategies that remain resilient under disaster conditions. This theoretical foundation underscores the necessity of hybrid approaches for advancing both MANET research and disaster-response planning.

LITERATURE GAPS

Although numerous mobility models have been proposed in the literature, only a limited subset has been explicitly tailored to emergency response scenarios. The majority of existing approaches were designed for general-purpose simulations, such as urban traffic or military manoeuvres, and therefore fail to capture the distinctive characteristics of Search-and-Rescue (SAR) operations. Several critical gaps can be identified.

1. Over-reliance on idealised movement patterns: Entity-based models, such as Random Waypoint or Gauss–Markov, emphasise stochastic independence, treating each node as an isolated actor. While this approach is useful for simulating crowds or pedestrian flows, it neglects the coordinated nature of SAR teams, where responders must balance autonomy with collective objectives (Sahu & Mishra, 2024). Conversely, group-based models, such as the Reference Point Group Mobility Model, assume rigid cohesion and synchronisation among nodes. This assumption contradicts the operational reality of SAR missions,

where responders frequently diverge from group trajectories to investigate hazards, assist victims, or transport equipment (Bodra & Amritanjali, 2019). The reliance on idealised movement patterns reduces the fidelity of simulations and risks misrepresenting network performance under disaster conditions (Manimegalai & Jayakumar, 2013; Kour & Ubhi, 2015).

2. Lack of contextual grounding: Only a handful of studies have incorporated real disaster settings as reference points for mobility modelling. Many simulations rely on abstract or synthetic environments, which fail to account for the geographical and environmental complexities of collapsed buildings, debris fields, or hazardous terrain (Kumar et al., 2024). Recent work has emphasised the importance of grounding mobility models in empirical disaster data, noting that contextual realism significantly improves the predictive validity of MANET performance evaluations (Goncalves et al., 2020). Studies such as Mahiddin et al. (2021) and Tang et al. (2025) further highlight that disaster-specific mobility data, drawn from real-world events, is essential for accurate modelling and prediction. Without such grounding, models risk producing results that are theoretically elegant but practically irrelevant (Amjad, 2013).

3. Insufficient integration of heterogeneous behaviours: SAR responders frequently switch between different modes of movement, including individual investigation, coordinated group traversal, and equipment transport. Most existing models do not incorporate these behavioural shifts, instead privileging either independence or cohesion. Hybrid approaches have begun to address this limitation, but many remain underdeveloped, lacking mechanisms to represent fluid transitions between behavioural states (Mnati et al., 2024). The absence of heterogeneous behavioural integration undermines the capacity of simulations to reflect the situational and role-dependent dynamics of SAR operations (Priyam & Yadav, 2024; Sarkar & Ali, 2025).

4. Underrepresentation of operational constraints: Disaster zones impose numerous constraints on mobility, including obstacles, debris, hazardous zones, and entry–exit points. These factors influence node trajectories and communication reliability but are rarely embedded into simulation frameworks (Pullin et al., 2018). Emerging research highlights the need to incorporate environmental constraints into mobility models to improve realism and ensure that MANET simulations reflect the operational challenges faced by responders (Muthukumar & Nagarajan, 2025). Studies such as Aschenbruck et al. (2004), Balart-Sanchez & Gutierrez-Preciado (2020), and Tokunaga & Ebara (2024) demonstrate that incorporating tactical and environmental constraints significantly enhances simulation fidelity. Without such integration, models risk oversimplifying the complexity of disaster environments (Chitra & Ranganayaki, 2019).

These limitations point to the need for a more realistic mobility model that reflects the fluid, situational, and role-dependent nature of SAR movement. A hybridised approach, grounded in empirical disaster data and capable of integrating heterogeneous behaviours and environmental constraints, offers a promising direction. Such a model would not only enhance the accuracy of MANET simulations but also provide actionable insights for designing resilient communication strategies in disaster-response planning.

PROPOSED HYBRID MOBILITY MODEL

The limitations of existing mobility models underscore the need for a framework that integrates both entity-based and group-based dynamics while embedding environmental and operational constraints. A hybrid mobility model for Search-and-Rescue (SAR) contexts must reflect the layered realities of disaster response, where autonomy and coordination coexist, and where environmental unpredictability shapes movement and communication patterns. The proposed model rests on four foundational principles that collectively advance the realism and applicability of MANET simulations in disaster environments (Figure 1).

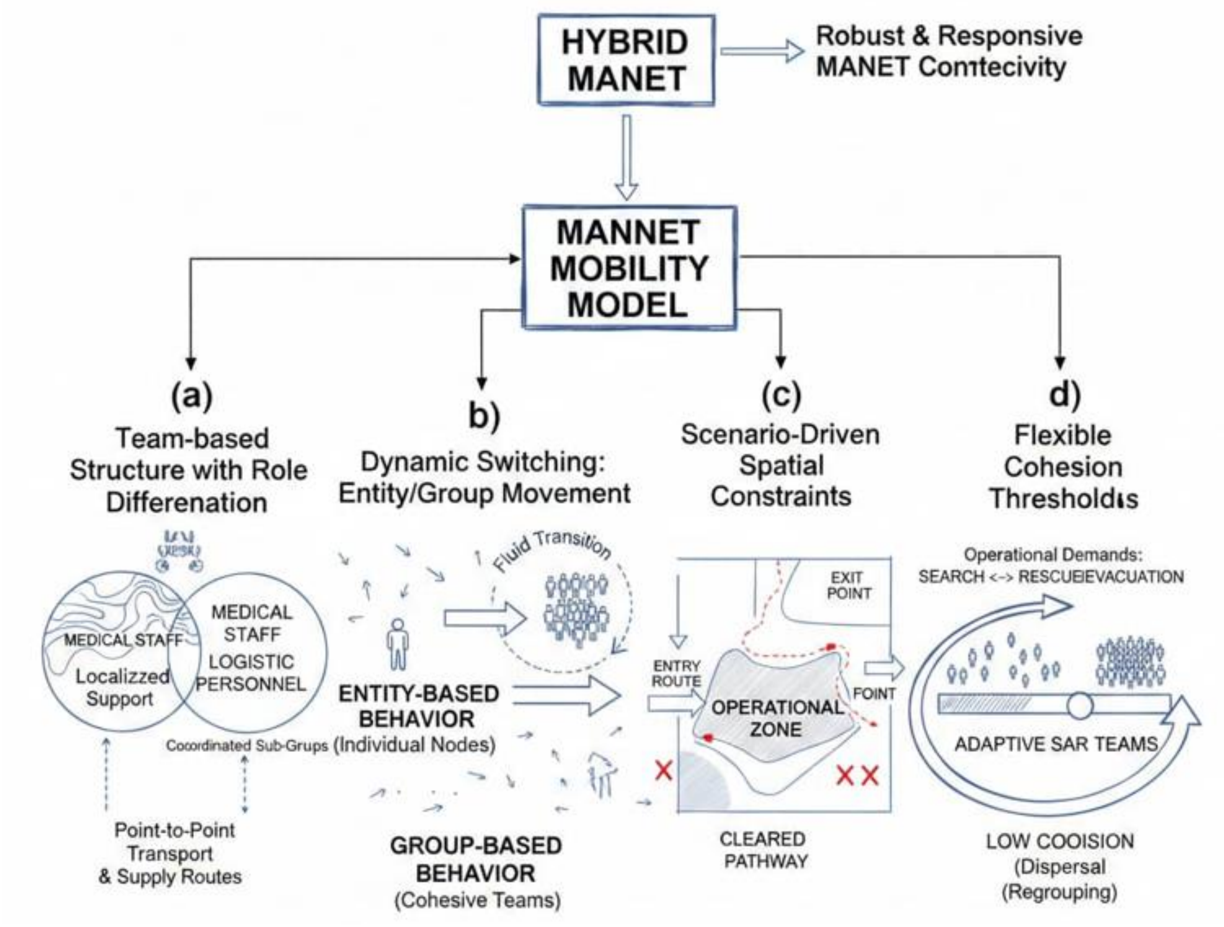

Figure 1: New Hybrid Mobility Model for Search-and-Rescue (SAR) Teams in Mobile Ad-Hoc Networks

Team-based structure with role differentiation

SAR teams are composed of subgroups such as medical staff, search technicians, and logistics personnel. Each subgroup follows characteristic movement patterns based on task requirements. For example, medical staff may cluster around casualty sites, while logistics personnel focus on transporting equipment along cleared pathways. Embedding role differentiation into the model ensures that simulations capture the heterogeneity of SAR behaviour, reflecting both task-driven autonomy and collective coordination (Bodra & Amritanjali, 2019). This principle also aligns with recent findings that role-specific mobility significantly influences communication reliability in disaster-response networks (Muthukumar & Nagarajan, 2025).

Dynamic switching between entity and group movement

One of the defining features of SAR operations is the ability of responders to temporarily behave as independent agents when carrying out specific tasks before rejoining group movement. The hybrid model incorporates mechanisms for dynamic switching, allowing nodes to transition fluidly between entity-based and group-based behaviours. This design reflects the operational reality of SAR missions, where responders diverge to investigate hazards or assist victims but remain tethered to team objectives (Mnati et al., 2024). Embedding this flexibility, the model enhances the accuracy of simulations and supports the evaluation of routing protocols under conditions of fluctuating cohesion.

Scenario-driven spatial constraints

Disaster environments impose unique spatial constraints, including defined entry routes, exit points, operational zones, and cleared pathways. The hybrid model incorporates these constraints to ground simulations in empirical disaster settings. For instance, lessons from Hurricane Katrina demonstrated how debris fields and collapsed infrastructure shaped responder mobility and communication reliability (Kumar et al., 2024). Integrating scenario-driven spatial features ensures that simulations reflect the environmental challenges faced by SAR teams, thereby improving the predictive validity of MANET performance evaluations (Goncalves et al., 2020).

Flexible cohesion thresholds

Unlike traditional group-based models that assume fixed boundaries, the hybrid framework allows group cohesion to expand or contract depending on operational demands. This principle reflects the adaptive nature of SAR teams, which may disperse widely during search phases and regroup tightly during rescue or evacuation tasks. Flexible cohesion thresholds enable simulations to capture the dynamic balance between autonomy and coordination, ensuring that MANET evaluations reflect the fluidity of real-world SAR operations (Pullin et al., 2018).

Conceptually, the hybrid mobility model represents SAR behaviour more holistically by embedding both collective coordination and individual task execution within a single framework. Integrating role differentiation, dynamic switching, spatial constraints, and flexible cohesion thresholds, the model advances both theoretical and practical domains. For MANET research, it provides a more realistic basis for evaluating routing protocols, connectivity resilience, and communication efficiency. For disaster-response planning, it offers actionable insights into how communication systems can be designed to remain robust under complex and unpredictable conditions. Ultimately, the hybrid framework bridges the gap between abstract modelling and operational reality, contributing to the development of communication strategies that are both theoretically rigorous and practically applicable.

CONTRIBUTIONS TO KNOWLEDGE

This conceptual study advances mobility modelling in disaster-response contexts by reframing Search-and-Rescue (SAR) movement as a hybrid behavioural system. It contributes to both theoretical development and applied research in Mobile Ad Hoc Networks (MANETs), offering a structured foundation for future simulation and empirical validation. Four key contributions are outlined below.

Reframing SAR mobility as a hybrid behavioural system

The study provides a theoretical basis for understanding SAR movement not as a singular pattern but as a layered behavioural system that integrates individual autonomy with coordinated group dynamics. Traditional models tend to privilege either stochastic independence or rigid cohesion, failing to capture the fluid transitions observed in real-world SAR operations (Mnati et al., 2024). Conceptualising SAR mobility as hybrid, the study introduces a framework that reflects the situational, role-dependent, and adaptive nature of responder movement. This reframing supports more realistic simulation design and enhances the interpretive validity of MANET performance evaluations.

Structured rationale for model integration

Rather than proposing an entirely new mobility model from scratch, the study offers a structured rationale for integrating existing entity-based and group-based models. This approach acknowledges the strengths of established frameworks while addressing their limitations through conceptual synthesis. The hybrid model leverages the stochastic flexibility of entity-based designs and the structural logic of group-based models, embedding mechanisms for dynamic switching and role differentiation (Bodra & Amritanjali, 2019). This integrative strategy promotes methodological efficiency and encourages researchers to build upon validated components rather than duplicating efforts.

Identification of mobility features influencing MANET performance

The study contributes to emergency communication research by identifying specific mobility features that affect MANET performance under high-stress conditions. These include dynamic role transitions, scenario-driven spatial constraints, and flexible cohesion thresholds. Embedding these features into the hybrid model, the study enhances the realism of simulation environments and supports the evaluation of routing protocols, connectivity resilience, and communication reliability (Muthukumar & Nagarajan, 2025). This contribution is particularly relevant for disaster-response planning, where communication breakdowns can have life-threatening consequences.

Establishment of a conceptual platform for simulation-based research

The hybrid model serves as a conceptual platform for future simulation-based studies. It provides a structured foundation for empirical research aimed at refining and validating hybrid mobility behaviours in SAR contexts. Researchers can use the model to test routing algorithms, assess network robustness, and explore the impact of environmental constraints on communication performance (Goncalves et al., 2020). Bridging theoretical modelling with operational realities, the study supports the development of MANET systems that are both technically sound and contextually responsive.

Altogether, these contributions position the hybrid mobility model as a significant advancement in mobility modelling and emergency communication research. The framework not only addresses existing gaps but also opens new avenues for interdisciplinary inquiry, simulation design, and disaster-response innovation.

IMPLICATIONS FOR RESEARCH AND PRACTICE

The hybrid mobility model proposed in this study carries significant implications for both research and practice.

Embedding behavioural complexity, environmental constraints, and role differentiation into a unified framework, the model offers a more realistic foundation for simulating Search-and-Rescue (SAR) operations in disaster environments. These implications extend across methodological refinement, simulation design, emergency planning, and operational strategy.

For researchers working in the field of Mobile Ad Hoc Networks (MANETs), the model underscores the necessity of aligning mobility simulations with real-world operational contexts. Traditional models often rely on abstract or idealised movement patterns that fail to capture the situational dynamics of SAR missions (Sahu & Mishra, 2024). The hybrid framework encourages researchers to incorporate heterogeneous behaviours, dynamic role transitions, and scenario-driven spatial constraints into simulation design. This alignment improves the accuracy of performance evaluations, particularly in assessing routing protocols, connectivity resilience, and communication latency under stress conditions (Mnati et al., 2024).

The model also provides a conceptual platform for empirical validation. Researchers can use it to design simulation studies that test the impact of mobility features on network performance, compare routing strategies under hybrid conditions, and explore the influence of environmental constraints on node behaviour. These studies can contribute to the development of context-sensitive MANET protocols and support the refinement of mobility models for other high-stakes domains, such as military coordination or humanitarian logistics (Muthukumar & Nagarajan, 2025).

For practitioners, particularly emergency planners, SAR coordinators, and communication system designers, the model offers actionable insights into how mobility modelling can inform operational strategy. Realistic simulations enable planners to anticipate connectivity gaps, identify vulnerable communication zones, and optimise deployment strategies based on terrain and task requirements (Goncalves et al., 2020). Reflecting the behavioural complexity of SAR teams, the model supports the design of communication infrastructures that remain resilient under unpredictable and hazardous conditions.

Simulation-driven insights can also enhance training and resource allocation. Emergency responders can engage with scenario-based simulations that reflect realistic movement patterns, improving preparedness and coordination. Planners can use model outputs to determine optimal equipment placement, route clearance priorities, and team composition based on mobility constraints. These applications contribute to more effective disaster-response planning and support the development of adaptive, role-sensitive communication systems.

In addition, the model encourages interdisciplinary collaboration between network engineers, behavioural scientists, and emergency management professionals. Bridging technical modelling with operational realities, it fosters a shared understanding of how mobility influences communication performance in disaster contexts. This collaboration can lead to the co-design of simulation tools, training platforms, and decision-support systems that are both technically robust and operationally relevant.

Overall, the hybrid mobility model advances the methodological precision of MANET research and enhances the strategic utility of mobility modelling in emergency response. Its implications extend beyond simulation fidelity, offering a foundation for innovation in disaster communication planning, training, and infrastructure design.

LIMITATIONS AND FUTURE RESEARCH

This paper is conceptual in scope. It sets out the theoretical foundation for a hybrid mobility model but does not attempt empirical validation at this stage. That absence is important to acknowledge: without grounding in simulation or field data, the model remains a descriptive framework rather than a tested solution. Making this limitation explicit, the study positions itself as a starting point for deeper inquiry rather than as a finished product.

Future research should build on this foundation by operationalising the model in simulation environments such as NS-3 or OMNeT++, drawing on disaster-specific datasets to test its robustness. Validation efforts could examine how heterogeneous behaviours, environmental constraints, and adaptive cohesion thresholds affect MANET performance metrics including routing efficiency, packet delivery, and connectivity resilience. Beyond simulation, field studies in contexts such as earthquake response, hurricane recovery, or urban search missions would provide valuable evidence of applicability. Extending the framework to other domains, such as humanitarian logistics, maritime rescue, or military coordination, would also demonstrate its broader relevance.

Framing this work as a conceptual platform, the paper invites empirical refinement and interdisciplinary collaboration, ensuring that future iterations of the model are both theoretically rigorous and operationally grounded.

CONCLUSION

Search-and-Rescue (SAR) operations demand communication systems that remain reliable under chaotic and unpredictable conditions. Disasters frequently compromise conventional infrastructure, leaving responders dependent on decentralised solutions such as Mobile Ad Hoc Networks (MANETs). The effectiveness of these networks depends on the realism of mobility models, which shape evaluations of routing protocols, connectivity resilience, and communication efficiency.

This paper has presented a conceptual foundation for a hybrid mobility model that more accurately reflects SAR behaviour in disaster environments. Integrating entity-based and group-based mobility characteristics, the proposed model addresses key limitations in existing frameworks. Entity-based models capture autonomy but oversimplify teamwork, while group-based models represent coordination yet assume rigid cohesion. The hybrid approach reconciles these shortcomings by embedding dynamic switching between behaviours, role differentiation, scenario-driven spatial constraints, and flexible cohesion thresholds.

The model contributes to knowledge by reframing SAR mobility as a hybrid behavioural system, offering a structured rationale for integrating existing models, and identifying mobility features that influence MANET performance under stress. It also establishes a conceptual platform for simulation-based research, enabling empirical studies to refine and validate hybrid approaches.

Future research should focus on validating the model through simulation and field studies, exploring adaptive variations, and extending its application to other emergency-response contexts. Bridging theoretical modelling with operational realities, the hybrid framework advances both MANET research and disaster-response planning, supporting the design of resilient communication systems capable of withstanding the unpredictability of SAR operations.

AUTHOR CONTRIBUTION

All authors contributed meaningfully to the development of this study and the preparation of the manuscript. The study design and conceptualisation of the hybrid entity–group mobility framework were undertaken by K.U.A. The simulation methodology, experimental design, and implementation using NS2 were collaboratively planned. Data analysis, interpretation of simulation results, and validation of findings were conducted collectively, with all authors contributing to critical discussion and refinement of the results. The manuscript was drafted by I.U.A., C.E.E. and K.O.O., with all co-authors providing critical revisions, intellectual input, and editorial feedback. All authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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