International Journal of Modern Computer Science and IT Innovations (IJMCSII)
eISSN: 3087-4289
Volume. 03, Issue. 03, pp. 01-29, March 2026"

Design, Simulation, and Performance Evaluation of a Hybrid Mobility Model for Search-and-Rescue Teams in Mobile Ad Hoc Networks

Ikenna Uzoma Ajere, MSc
Department of Information Technology, Federal University of Technology, Owerri, Nigeria; and Department of Interdisciplinary Research & Statistics, PENKUP Research Institute, Birmingham, United Kingdom.

Kennedy Oberhiri Obohwemu, PhD
Department of Interdisciplinary Research and Statistics, PENKUP Research Institute, Birmingham, United Kingdom.

Festus Ituah, PhD
School of Health and Sports Science, Regent College, London, United Kingdom; and Department of Interdisciplinary Research & Statistics, PENKUP Research Institute, Birmingham, United Kingdom.

Oluwafemi Emmanuel Ooju, MSc
World Health Organisation, Abuja, Nigeria; and Department of Interdisciplinary Research & Statistics, PENKUP Research Institute, Birmingham, United Kingdom.

Oladipo Vincent Akinmade, MPH
Digital Health and Rights Project (Center for Interdisciplinary Methodologies, CIM), University of Warwick, Coventry, United Kingdom; and Department of Interdisciplinary Research & Statistics, PENKUP Research Institute, Birmingham, United Kingdom.

Solomon Atuman, MPH
FHI 360; and Department of Interdisciplinary Research & Statistics, PENKUP Research Institute, Birmingham, United Kingdom.

Jennifer Adaeze Chukwu, PhD
World Health Organization, United Nations House, Abuja, Nigeria; and Department of Interdisciplinary' and 'Studies & Statistics, PENKUP Research Institute, Birmingham, United Kingdom.

Corresponding Author: Ikenna Uzoma Ajere, Department of Information Technology, Federal University of Technology, Owerri, Nigeria. Ajere@futo.edu.ng

Article Received: 01/11/2026, Article Accepted: 02/24/2026, Article Published: 03/03/2026
DOI: https://doi.org/10.55640/ijmcsit-v03i03-01

© 2026 Authors retain the copyright of their manuscripts, and all Open Access articles are disseminated under the terms of the Creative Commons Attribution License 4.0 (CC-BY), which licenses unrestricted use, distribution, and reproduction in any medium, provided that the original work is appropriately cited.

ABSTRACT

Mobility modelling plays a pivotal role in evaluating the performance of Mobile Ad Hoc Networks (MANETs), as the movement patterns of nodes strongly influence routing efficiency, connectivity, and network stability. Existing mobility models, particularly entity and group-based frameworks, have proven useful in simulating various MANET applications but remain limited in capturing the complex movement behaviour characteristic of Search-and-Rescue (SAR) operations in disaster scenarios. This study proposes a realistic hybrid mobility model that integrates the essential features of both entity and group mobility paradigms to better represent the coordinated yet flexible dynamics of SAR teams.

Three sets of simulations were performed using the Network Simulator 2 (NS2). The first and second simulations focused on generating and combining existing entity and group mobility patterns using the BonnMotion tool, resulting in two composite models (Real1 and Real2). The third simulation compared these models using AODV and

DSDV routing protocols under varying node mobility levels and traffic conditions. Key performance metrics, including relative mobility, node degree, partition count, link duration, packet delivery ratio (PDR), throughput, and average end-to-end delay, were analysed.

Results demonstrate that it is feasible to concatenate existing mobility models into a coherent hybrid framework. Among the developed models, Real2 exhibited superior performance in most test conditions, yielding higher PDR, lower delay, and more stable connectivity than its constituent models. These findings confirm that the performance of MANETs is highly dependent on mobility realism. Consequently, selecting a model that accurately reflects the behavioural characteristics of the target scenario is essential for credible MANET performance evaluation in emergency response contexts.

KEYWORDS

Mobile Ad Hoc Networks (MANETs); Mobility Modelling; Hybrid Mobility Model; Search-and-Rescue; Disaster Scenarios; AODV; DSDV; NS2 Simulation; Performance Evaluation; Routing Protocols

INTRODUCTION

After every major catastrophe, such as a large-scale fire outbreak, earthquake, hurricane, or tornado, search-and-rescue (SAR) teams are rapidly deployed to locate survivors, provide immediate medical support, and transport casualties to hospitals for resuscitation and recovery. Those who tragically lose their lives are often buried in mass graves as part of post-disaster management. In these chaotic environments, communication infrastructures are typically damaged or destroyed, leaving responders with limited means to coordinate their operations. To bridge this communication gap, it becomes imperative to deploy a temporary, self-sustaining communication system capable of supporting mobility, adaptability, and real-time data exchange.

A Mobile Ad Hoc Network (MANET) is often used in such circumstances because of its infrastructure-less nature, rapid deployability, and minimal administrative overhead (Mabina, 2025). In a MANET, each node acts not only as a source or destination but also as a router responsible for route discovery, maintenance, and packet forwarding, thereby enabling dynamic, decentralized connectivity among mobile devices (Ramphull et al., 2021; Rahman et al., 2023). Figure 1 shows a typical MANET setup in which mobile nodes interact through multi-hop wireless links to maintain connectivity even in the absence of fixed infrastructure.

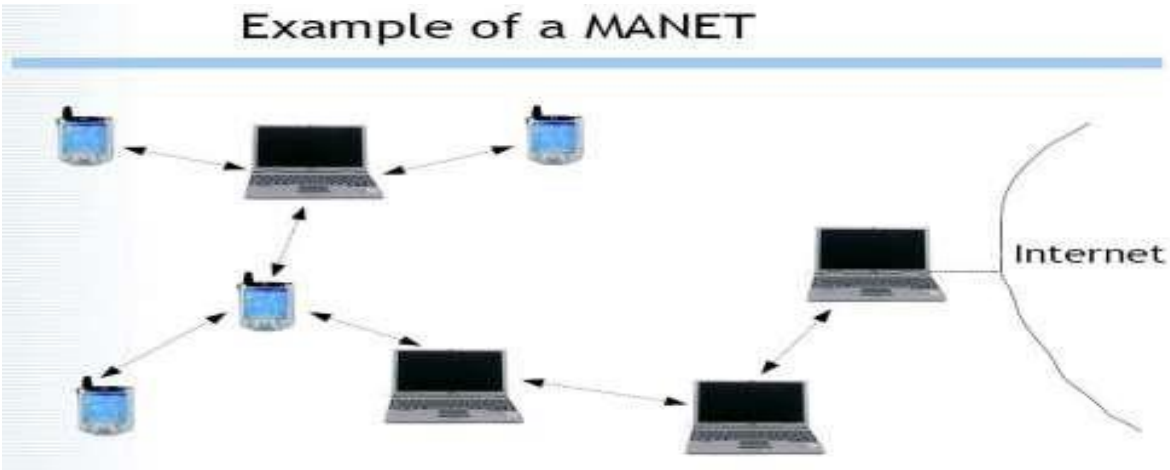


Figure 1. Setup of a Mobile Ad Hoc Network (MANET)

A typical SAR team is composed of multiple specialized units, including medical personnel, psychological support

staff, transport coordinators, and rescue specialists (Wilson et al., 2023). Each of these units operates within a specific functional domain, and their movements are influenced by distinct operational objectives. Consequently, the overall mobility of the SAR team reflects a combination of diverse, interdependent movement patterns. For example, while the medical unit may move between casualty zones and field hospitals, the rescue team navigates unstable terrain in unpredictable ways. Such variability introduces a high degree of complexity in modelling their movement behaviour. The accuracy and realism of a mobility model depend largely on how effectively it represents these real-world dynamics (Jindal et al., 2025; Zhang et al., 2025).

The more closely a model mirrors actual human and vehicular motion in a disaster zone, the more reliable its simulation results and the better its predictive performance in network evaluation (Mahiddin, Affandi & Mohamad, 2021). Existing research underscores that the choice of mobility model significantly affects MANET performance in terms of throughput, delay, packet delivery ratio, and route stability (Eltahlawy et al., 2023). A model that accurately captures the unpredictable and heterogeneous movement of nodes within a SAR context provides a stronger basis for evaluating and selecting appropriate routing protocols (Alsayyed et al., 2025). Figure 2 illustrates the major classifications of MANET routing protocols (reactive, proactive, and hybrid), highlighting how different strategies manage routing information.

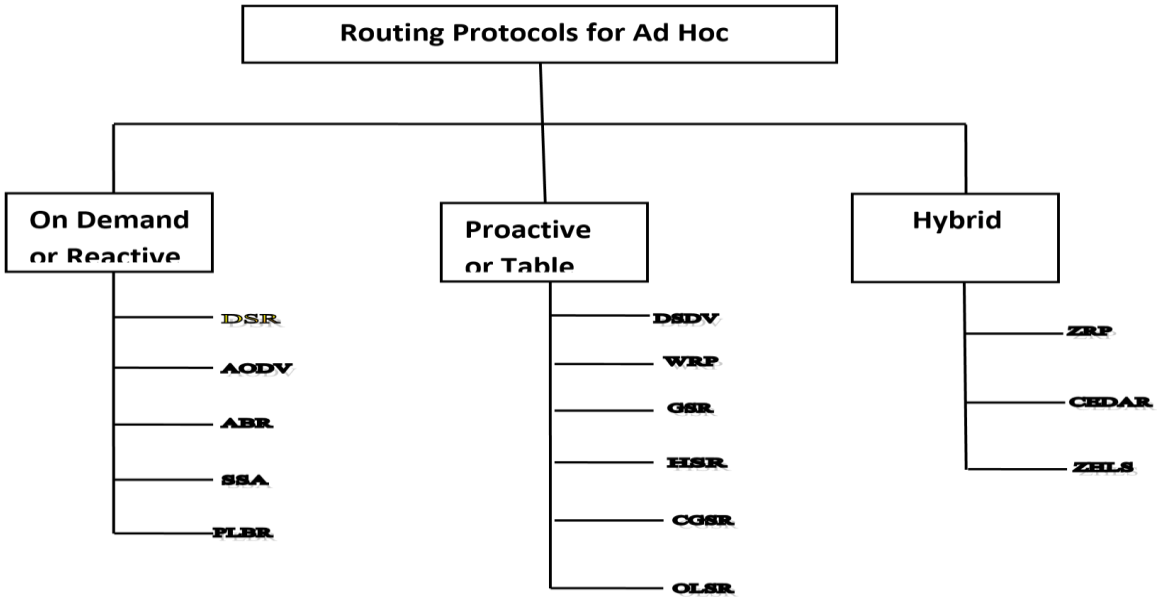


Figure 2. Classification of Mobile Ad Hoc Routing Protocols.

Commonly used mobility models, such as Random Waypoint, Random Walk, Random Direction, Reference Group, Gauss–Markov, and Manhattan Grid, each simulate specific types of movement but fall short of representing the full range of behaviours observed in real SAR operations (Kour & Singh, 2022). The Random Waypoint model, for instance, assumes independent node movement and sharp turns, which rarely occur in coordinated team-based rescue operations (Ammar et al., 2021). Similarly, group models like the Reference Point Group model assume fixed group memberships, whereas SAR teams are fluid, and members may join, separate, or reconfigure depending on situational demands (Mohamed, Hamza & Sariot, 2017).

Disaster response environments also exhibit features not captured in traditional models, including dynamic obstacles, fluctuating node densities, and varied communication ranges (Matracia et al., 2022). For instance, collapsed buildings or debris may obstruct line-of-sight radio propagation, while certain areas, such as hospitals, command centres, or casualty treatment zones, naturally attract higher node concentrations due to operational priorities (Al-Allaq, Shakir & Charafeddine, 2025). Furthermore, communication patterns within SAR missions are hierarchical: commanders coordinate across teams, team leaders communicate within groups, and individual members exchange peer-to-peer updates. These multi-layered patterns demand a hybrid modelling approach that combines the flexibility of entity

mobility with the cohesion of group mobility to capture both individual autonomy and collective coordination (Scatà, 2025).

This study is motivated by the need to develop a more realistic and adaptable mobility model that captures the intricate movement behaviour of SAR teams in post-disaster scenarios. Using the 2005 Hurricane Katrina disaster as a case study, the research proposes a hybrid mobility model that merges existing entity and group mobility models to better represent the real-world movement of responders in a disaster area. Hurricane Katrina remains one of the most documented examples of communication breakdown in emergency response history, with traditional infrastructure collapsing and ad hoc wireless systems becoming the only viable means of coordination (Karaman et al., 2025). Figure 3 depicts the route establishment process in the Ad hoc On-Demand Distance Vector (AODV) protocol, one of the reactive routing mechanisms assessed in this study.

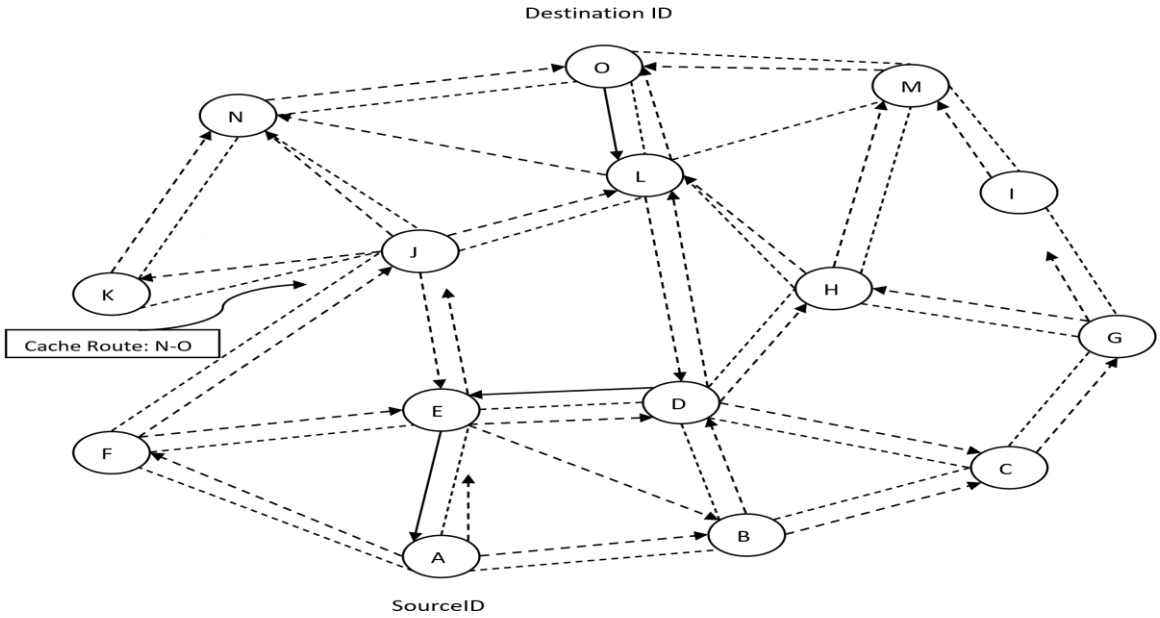


Figure 3. *Route Establishment in Ad hoc On-Demand Distance Vector (AODV) Protocol.*

Key:

Network Link

RouteReq

RouteReq

Building on the conceptual hybrid mobility framework proposed in Ajere et al. (2026), this study advances the work by implementing and empirically evaluating hybrid mobility models using NS2. In contrast to the earlier theoretical formulation, the present study operationalises the hybrid principles through the construction of two composite mobility scenarios (Real1 and Real2) generated by concatenating and integrating established entity-based and group-based models via the BonnMotion tool. These models are subjected to extensive simulation under varying mobility levels, traffic loads, and routing protocols, enabling a rigorous assessment of how hybridised movement patterns influence MANET performance in disaster-response environments. Through this empirical approach, the study provides concrete evidence of the feasibility, behaviour, and performance implications of hybrid mobility modelling, thereby transforming the conceptual framework into a validated simulation-based methodology.

The research methodology for this study involves concatenating established entity and group mobility models using two distinct integration techniques implemented in the Network Simulator 2 (NS2) platform. The resulting models are compared with their constituent models using both link-layer and protocol-level metrics, allowing a comprehensive performance evaluation (Ahmed et al., 2025). The study further examines how variations in mobility

levels (high and low) and traffic source density affect model performance under two widely used routing protocols: Ad hoc On-Demand Distance Vector (AODV) and Destination-Sequenced Distance Vector (DSDV). Figure 4 shows the route establishment process for DSDV, a proactive routing protocol that maintains continuous topology updates across nodes.

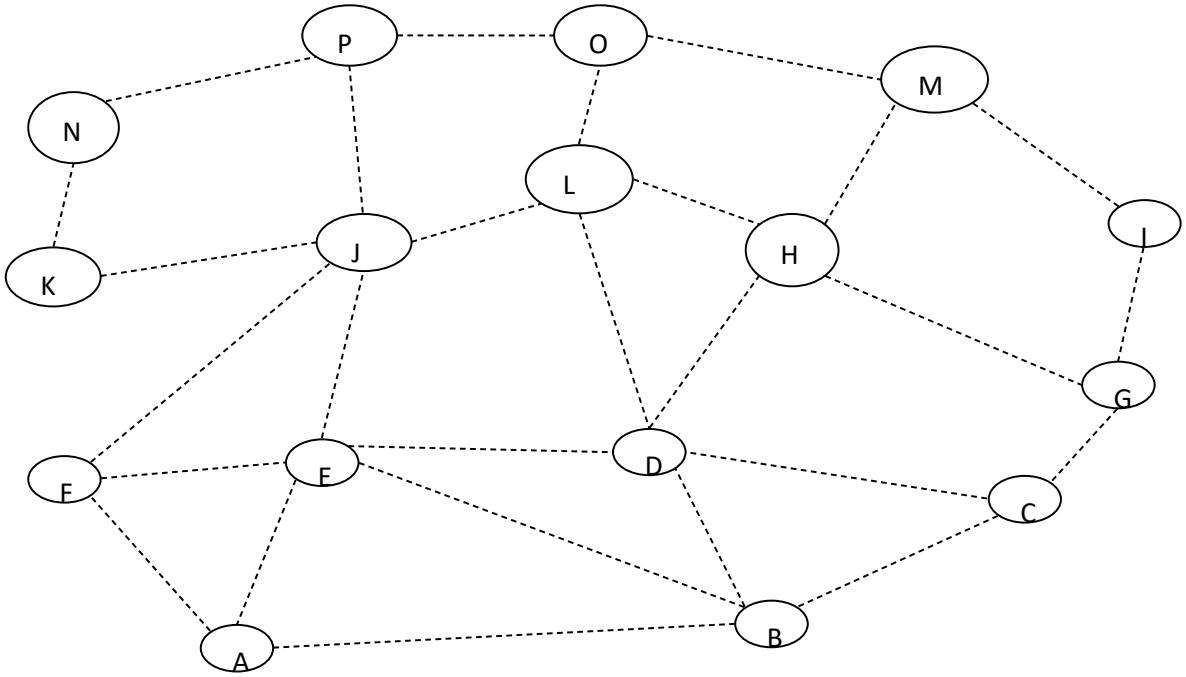


Figure 4. *Route Establishment in Destination-Sequenced Distance Vector (DSDV) Protocol.*

The DSDV protocol maintains continuous routing updates between nodes by exchanging periodic table information across the network (Ansari, Ishak & Ammar, 2025). Each node keeps a routing table that lists all reachable destinations, their next-hop nodes, hop counts, and sequence numbers that indicate route freshness. Table 1 presents an example of a routing table for a single node (Node A) within the network, illustrating how DSDV maintains consistent topology awareness across all nodes.

Table 1. *Routing Table for node A*

Destination	Next Node	Distance (Hops)	Sequence Number
B	B	1	22
C	B	2	26
D	E	2	32
E	E	1	134
F	F	1	144
G	B	3	162
H	E	3	170
I	B	4	186
J	F	2	142
K	F	3	176
L	E	3	190
O	E	4	198
M	E	4	214
P	E	3	256

As Table 1 demonstrates, each node in a DSDV network maintains detailed information about all possible routes, ensuring that up-to-date paths are available at all times. This proactive updating mechanism reduces route discovery delays but increases control overhead, especially in large or highly mobile networks (Reddy & Dhananjaya, 2022).

To address such limitations, hybrid routing protocols were developed, combining proactive and reactive features for greater scalability. Figure 5 illustrates the Zone Routing Protocol (ZRP), a hybrid scheme that integrates both mechanisms to optimise performance under dynamic conditions. In addition, hybrid protocols such as the Zone Routing Protocol (ZRP) incorporate both strategies to optimise communication efficiency in highly mobile networks. Figure 5 illustrates how ZRP divides a MANET into routing zones, enabling intra-zone proactive updates and inter-zone on-demand communications.

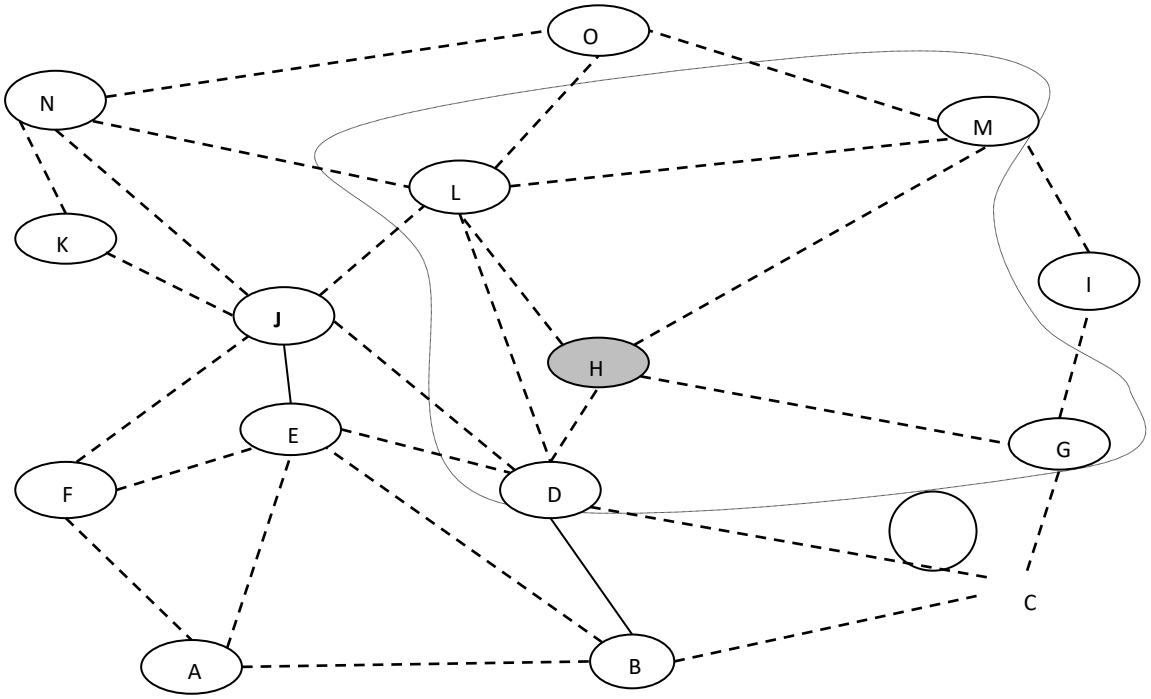


Figure 5. *Routing Zone for Node H in Zone Routing Protocol (ZRP).*

In real SAR missions, mobility patterns vary widely based on environmental conditions, mission urgency, and resource availability. High-mobility scenarios may occur when multiple rescue units are actively moving between incident sites and hospitals, whereas low-mobility conditions may dominate during medical triage or coordination phases. Similarly, the number of active communication sources may fluctuate with mission phases, influencing bandwidth usage, latency, and packet delivery rates. Analysing model performance across these dynamic parameters offers valuable insights into network robustness and adaptability (Kagai et al., 2024).

The uniqueness of this study lies in its synthesis of homogeneous mobility models into a composite framework that more accurately represents the diverse operational dynamics of search-and-rescue teams. Figure 6 presents the Random Waypoint model, which forms one of the entity-level building blocks of the proposed hybrid approach.

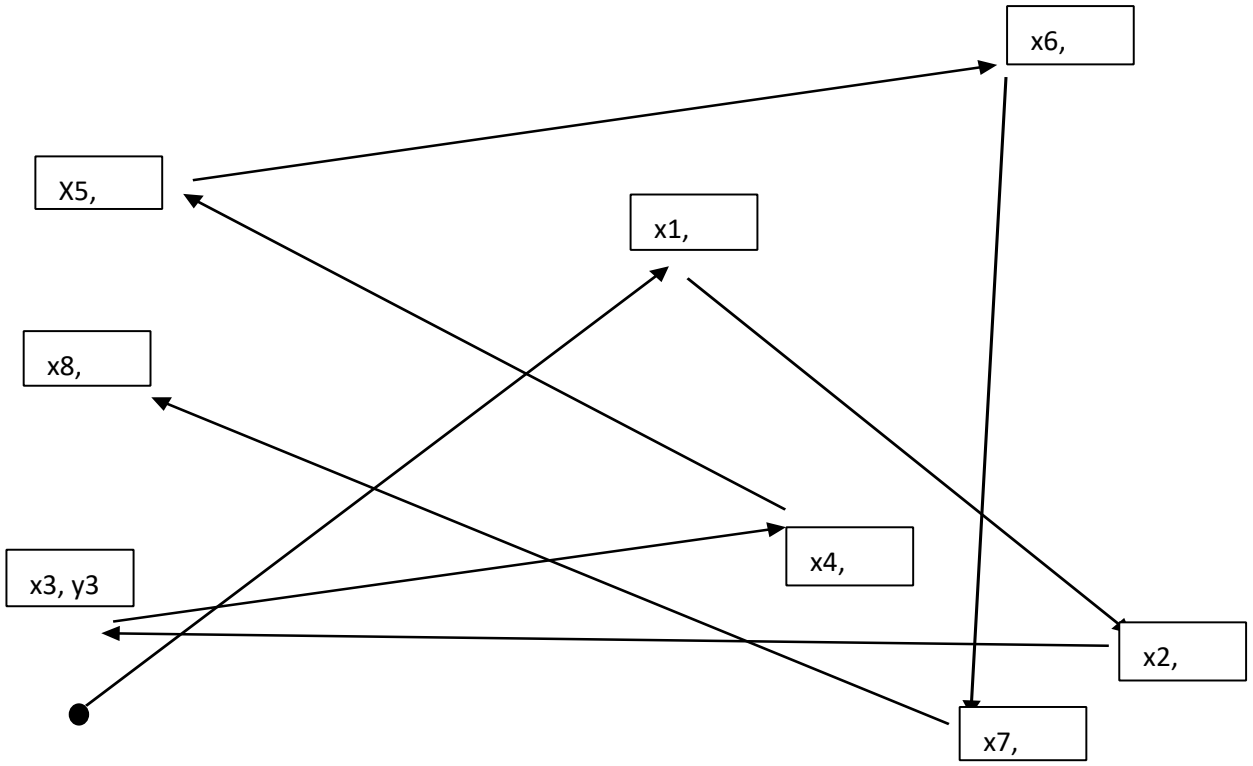


Figure 6. *Node Movement Pattern in Random Waypoint Mobility Model*

To account for constrained, path-dependent movements in structured environments such as urban disaster zones, the Manhattan Grid model (Figure 7) is incorporated. This model simulates nodes moving along intersecting pathways resembling city blocks, a common characteristic in metropolitan SAR operations.

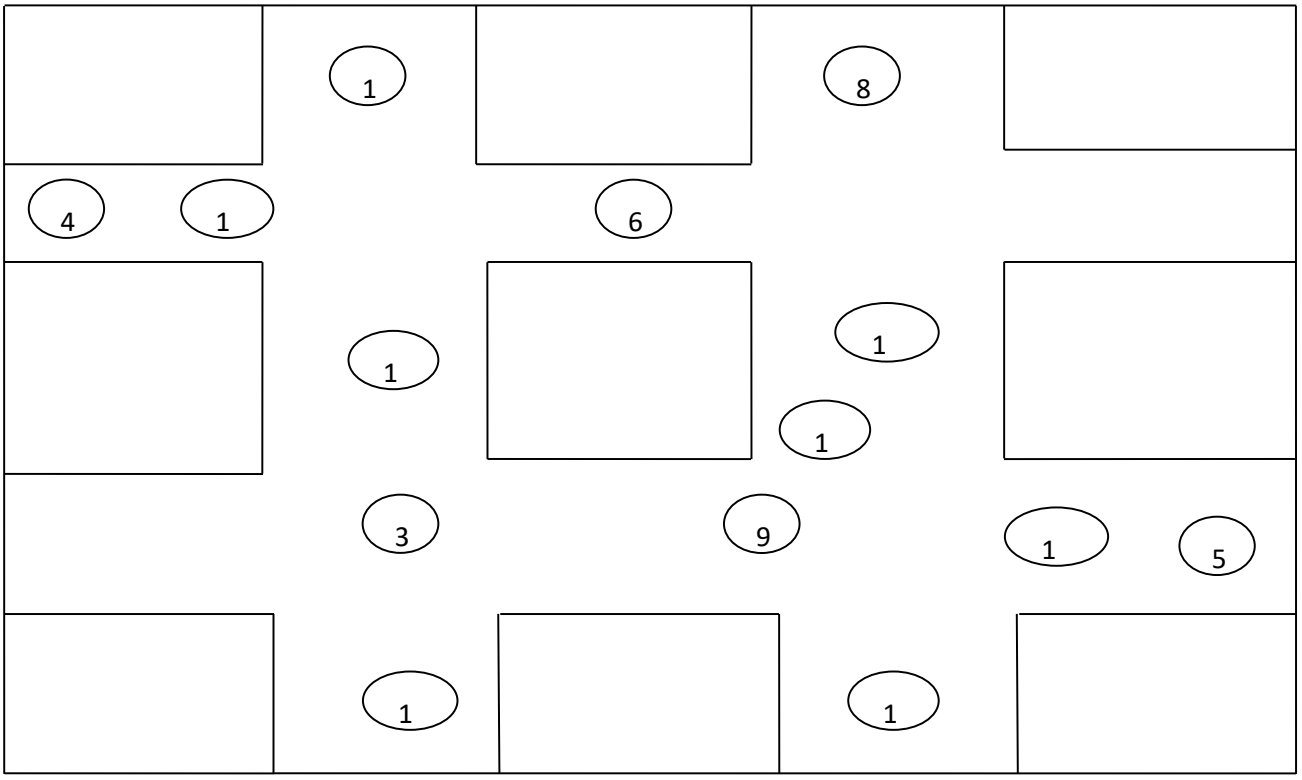


Figure 7. *Node Movement Pattern in Manhattan Grid Mobility Model.*

Finally, Figure 8 illustrates the Reference Point Group Mobility (RPGM) model, which depicts group-coordinated movement where each node follows the motion of a group leader, an essential concept for modelling team-based SAR dynamics.

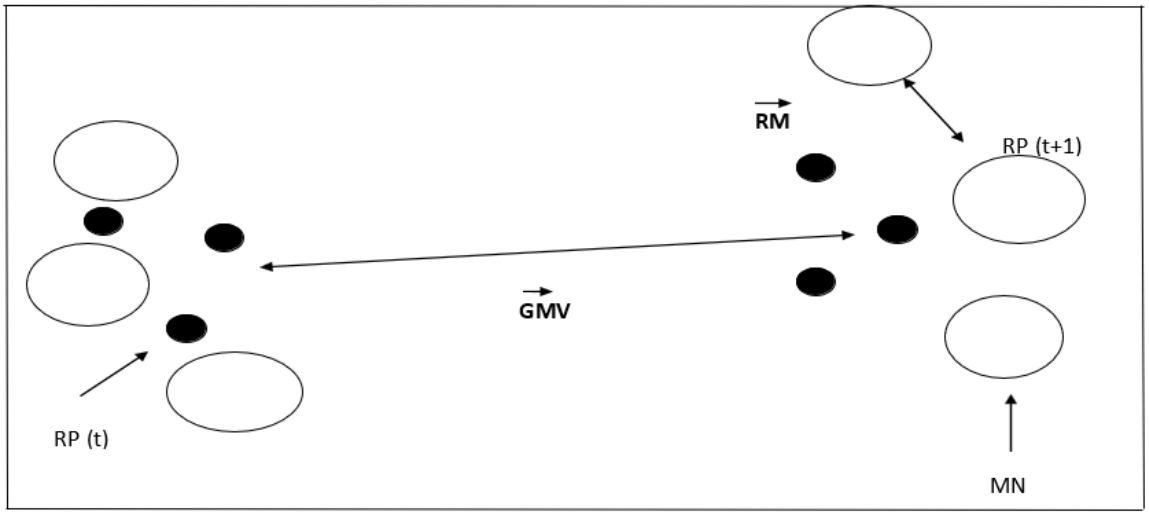


Figure 8. *Node Movement Pattern in Reference Point Group Mobility Model.*

Blending entity-based randomness with group-based coordination, the proposed hybrid model achieves a higher degree of realism in reflecting the fluid, interdependent motion of SAR responders. This integrated approach provides a novel contribution to MANET research by offering a more representative simulation of post-disaster communication environments. The ultimate aim is to improve routing efficiency, ensure consistent connectivity, and enhance overall situational awareness during emergency response operations.

Thus, this research introduces an integrated mobility model that addresses the limitations of existing approaches by capturing both individual and collective behaviours observed in real-life SAR missions. Through detailed simulation and comparative performance analysis, the study aims to establish a more reliable basis for evaluating MANET routing protocols in disaster contexts. By achieving this, it contributes not only to academic understanding of mobility modelling but also to practical disaster management strategies, where efficient communication can mean the difference between life and death.

METHODOLOGY

Three sets of simulations were conducted, each adopting a distinct methodological approach. Simulations 1 and 2 created new mobility models by combining existing entity and group mobility models, while Simulation 3 evaluated and compared the performances of these models under varying network conditions. Specifically, Simulation 3 examined routing performance using the Ad hoc On-Demand Distance Vector (AODV) and Destination-Sequenced Distance Vector (DSDV) protocols across different node mobility levels and traffic loads.

Hurricane Katrina Disaster Scenario

A real-life disaster scenario, the August 2005 Hurricane Katrina, was selected as the basis for this study. Hurricane Katrina was one of the deadliest hurricanes in U.S. history and among the strongest natural disasters ever recorded. It affected multiple states including Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, and Ohio, extending into the Gulf of Mexico. The hurricane caused approximately 1,836 fatalities and was initially rated Category 5 on the Saffir–Simpson scale before weakening to Category 3 at landfall (Whatley, 2023).

This study focused on New Orleans, Mississippi, one of the most severely affected areas. New Orleans covers approximately 181 square miles, with a 2005 census population of 454,863. Although there were no precise records of the number of search-and-rescue (SAR) workers deployed, an estimated 3,000 responders were assumed for

modelling purposes, based on the city's area and the disaster's magnitude. This estimate aligns with reports of large-scale federal and nongovernmental interventions documented in several reports (Singh et al., 2022; Robertson, 2025).

To maintain computational efficiency while preserving the real-world node density, the simulated environment was scaled down proportionally to 470 × 470 square meters with 30 nodes representing the 3,000 SAR workers. This spatial and density relationship provided a realistic approximation of the physical scenario within the Network Simulator 2 (NS2) environment.

Simulation 1: BonnMotion Chain Scenario Method

Simulation 1 utilised the BonnMotion Chain Scenario technique. The BonnMotion mobility generator, developed by the Communication Systems Group at the University of Bonn, Germany, is a Java-based tool for creating and analysing mobility scenarios in wireless ad hoc networks (Pasandideh et al., 2022). It supports scenarios in which mobile nodes behave differently depending on their positions, producing concatenated models where the final position of a mobile node in the (P–1)th scenario becomes the initial position in the Pth scenario.

Three entity mobility models (Random Waypoint (RWP), Manhattan Grid (MG), and Gauss–Markov (GM)) were specified with parameters chosen to reflect realistic movements in a disaster zone. These models were concatenated to yield individual movement pattern files and a composite movement file referred to as Real1, which integrates characteristics of all constituent models.

Network Simulator 2 (NS2), an object-oriented discrete event simulator developed at the University of California, Berkeley (Smera & Sandeep, 2022), was used for the simulation. Figure 9 provides a screenshot of the NS2 Network Animator (NAM) interface used for visualising node mobility, link formation, and packet transmission.

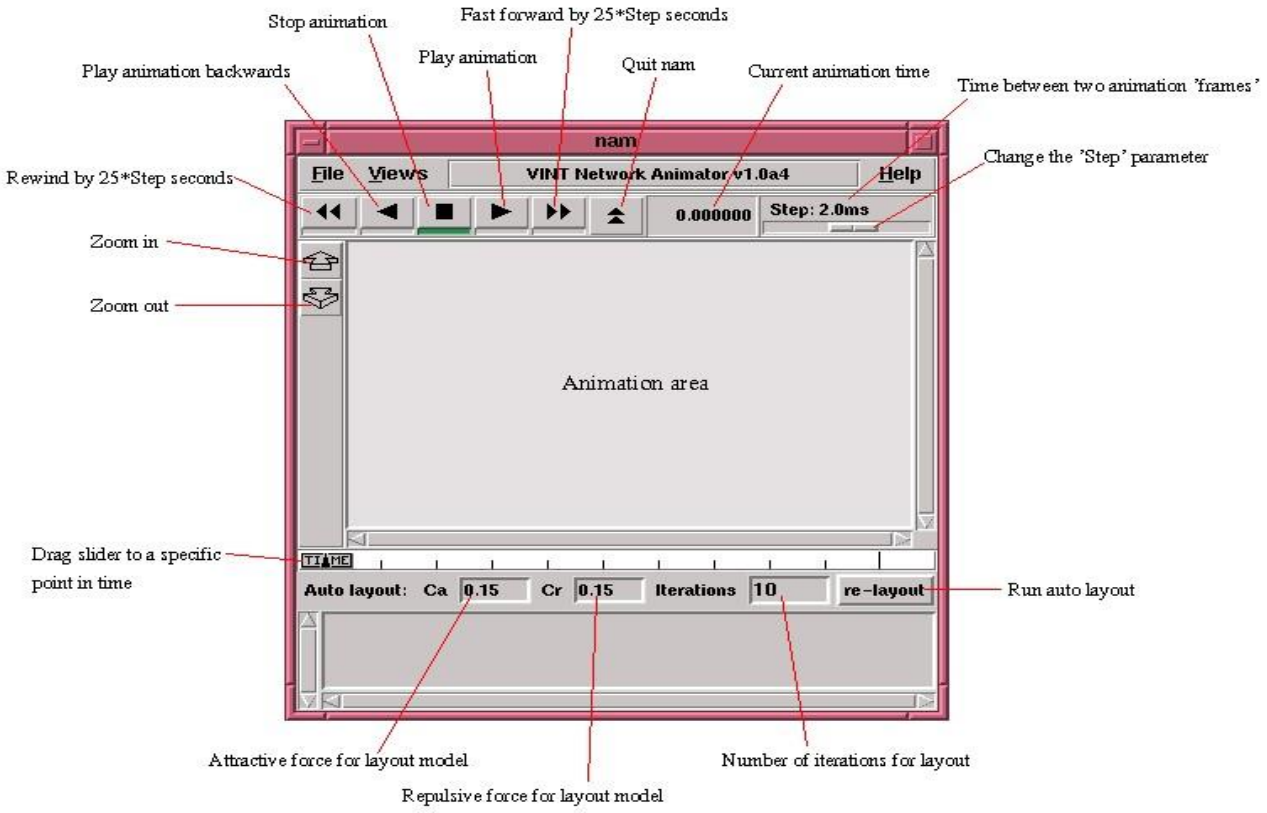


Figure 9. Screen shot of the NS2 Network Animator tool.

Table 2 presents the parameters used in Simulation 1.

Table 2. *Parameters for Simulation 1.*

Parameter Type	Parameter Value
Area	470 × 470 m²
Number of Nodes	30
Maximum Speed	5 m/s
Duration	6,000 seconds
Transmission Range	50, 100, 150, 200, 250 m
Mobility Models	RWP, MG, GM

A total of 40 simulation runs were performed to achieve statistically stable averages. The resulting movement files (. params) were analysed using the BonnMotion Statistics application to compute mobility and link metrics across the transmission ranges specified in Table 2.

Mobility Metrics

Relative Mobility (M) of node pairs was evaluated to quantify the effect of node velocity differentials on connectivity over time. Let l(a,t) and l(b,t) denote the positions of nodes a and b at time t. The instantaneous relative velocity v(a,b,t) is defined as:

$$V(a,b,t) = d/dt\ [\ l(a,t) - l(b,t)\ ] \qquad (1)$$

The relative mobility between nodes a and b over an observation window T is given by:

$$M_ab = (1/T) \int |\ v(a,b,t)\ |\ dt, \quad t_0 \le t \le t_0 + T \qquad (2)$$

Aggregating over all distinct node pairs yields the scenario-level relative mobility:

$$M = (2 / (n\ (n - 1))) \ \ \Sigma_\{a=1\}^\{n\}\ \Sigma_\{b=a+1\}^\{n\}\ \ M_ab \qquad (3)$$

Here, n is the number of nodes and |a,b| are distinct node pairs. Relative Mobility is independent of transmission range and captures the inherent motion dynamics of the scenario.

Link Metrics

To characterise structural properties of the network under mobility, the following link-level metrics were computed:

- Average Node Degree: the expected number of neighbours of a node, defined as Node Degree = ((n − 1) × Area_of_Transmission) / Area_of_Network

- Average Number of Partitions: indicates network connectivity; a value of 1 implies the network remains connected, while higher values indicate fragmentation.

- Degree of Separation: the probability that two randomly selected nodes are connected at a random time instant.

- Average Link Duration: the mean time that a link remains active before breakage (considering links active after start and inactive before simulation end).

Simulation 2: Composite Entity–Group Mobility Model

Simulation 2 incorporated the Reference Point Group Model (RPGM) to capture coordinated team movements among

SAR units. One-third of nodes followed RWP (nodes 0–9), one-third RPGM (nodes 10–19), and one-third GM (nodes 20–29). The merged mobility traces generated a composite scenario termed Real2. Figure 10 summarises the Simulation 2 workflow.

The nam files for the mobility models used in the simulation are shown in Figures 10-15.

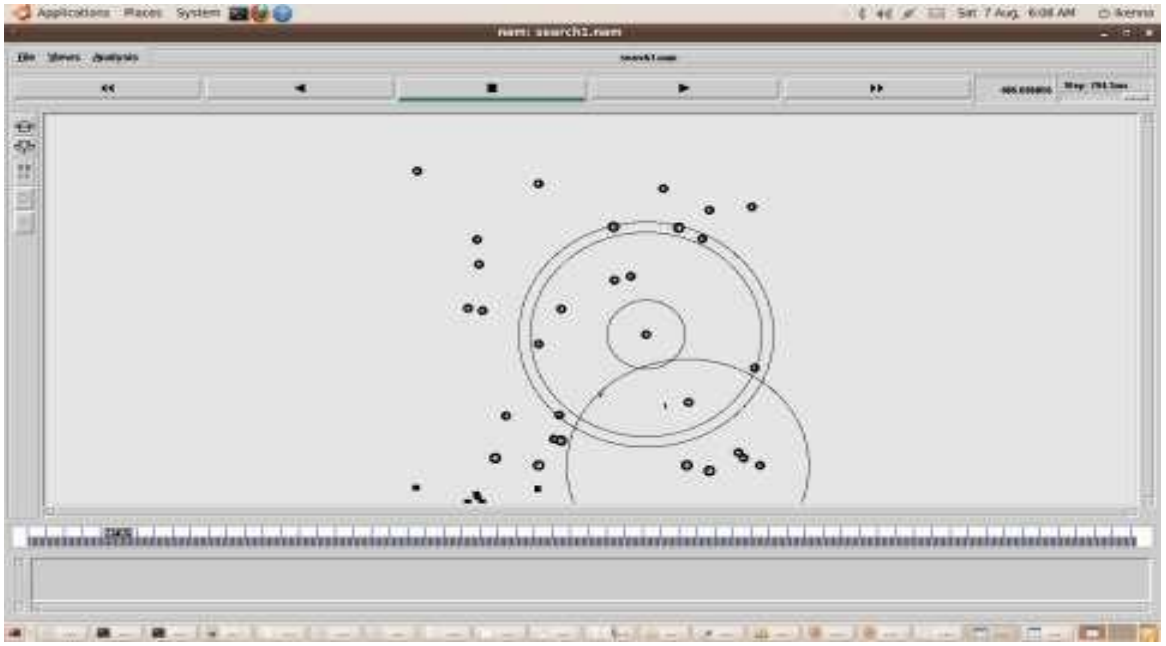


Figure 10. Screenshot of the NAM file showing the movement of nodes in GM Model

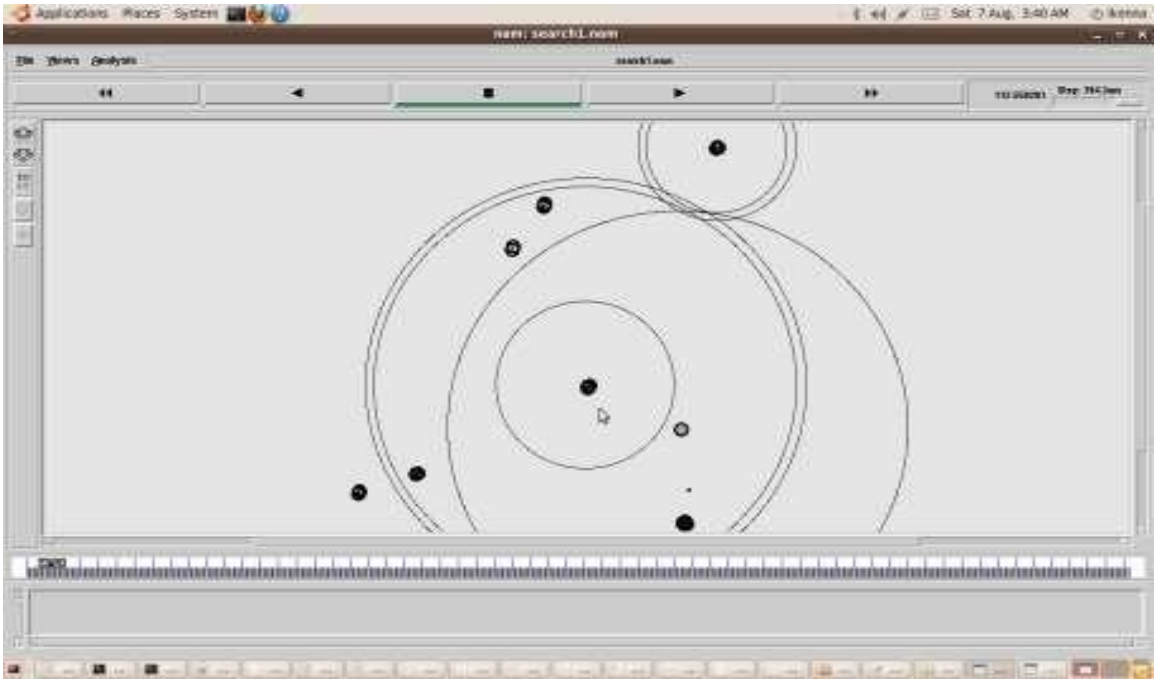


Figure 11. Screenshot of the NAM file showing the movement of nodes in RPGM

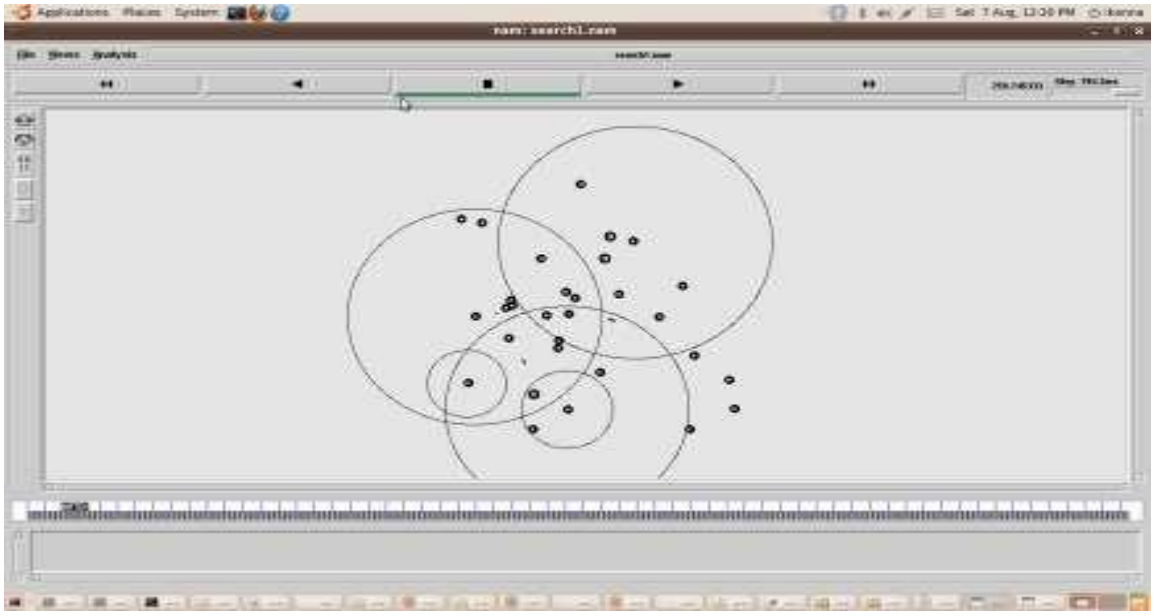


Figure 12. Screenshot of the NAM file showing the movement of nodes in RWP model

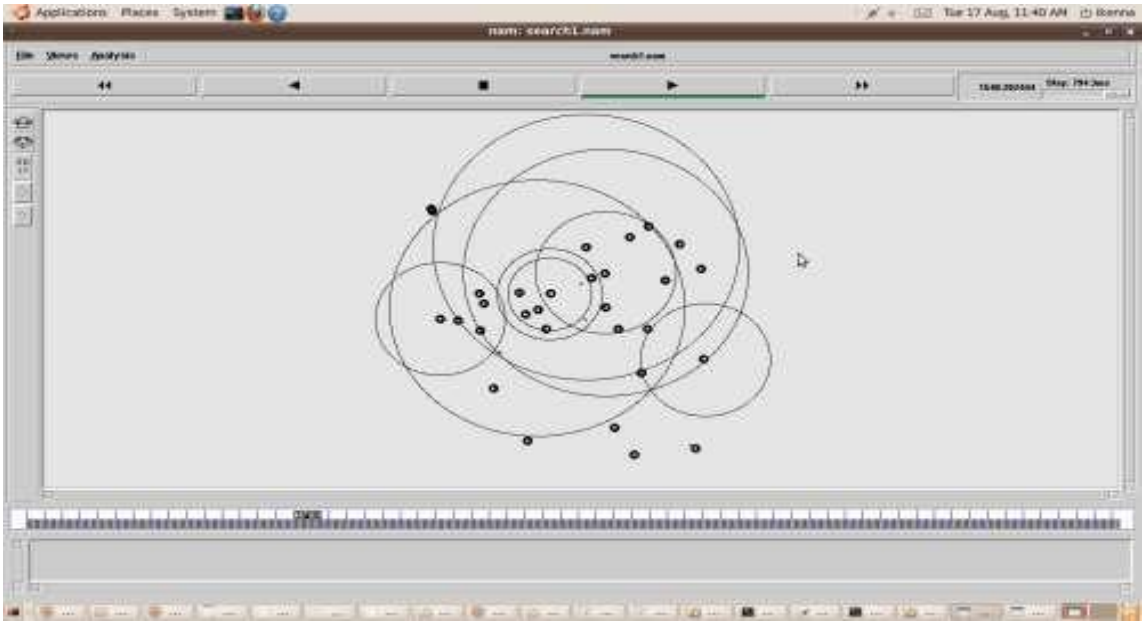


Figure 13. Screenshot of the NAM file showing the movement of nodes in MG model

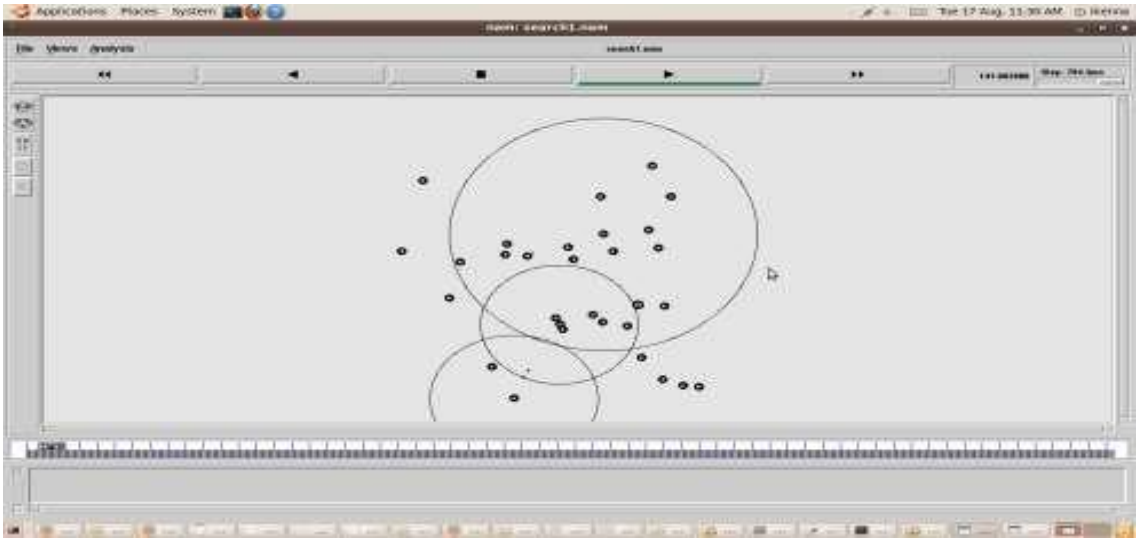


Figure 14. Screenshot of the NAM file showing the movement of nodes in Real2 model

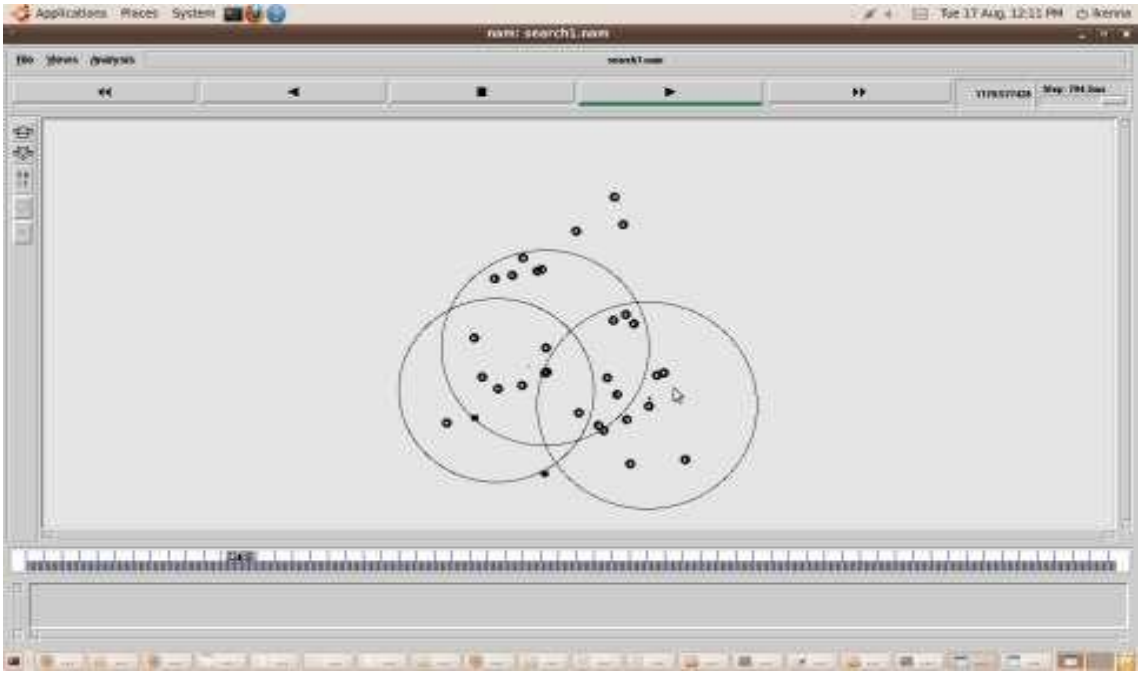


Figure 15. Screenshot of the NAM file showing the movement of nodes in Real1model

Trace files produced by NS2 TCL scripts were analysed using TraceGraph and a Java post-processor to compute protocol-dependent metrics.

Protocol-Dependent Metrics

- Number of Sent Packets: total packets generated by source nodes.
- Number of Received Packets: packets successfully received at destination nodes.
- Average End-to-End Delay (AEED):

$$AEED = (\Sigma (t_received - t_transmitted)) / N \qquad (4)$$

where N is the total number of received packets. Lower AEED reflects more efficient forwarding.

• Packet Delivery Ratio (PDR): PDR = (Total Received Packets) / (Total Sent Packets). Higher PDR indicates more stable links and routing.
• Throughput: cumulative bits successfully received at destination per second over the simulation duration.

Table 3 summarises the parameters used in Simulation 2.

Table 3. *Parameters for Simulation 2.*

S/No.	Parameter Type	Parameter Value
1	Area	470 × 470 m²
2	Number of Nodes	30
3	Traffic Type	Constant Bit Rate (CBR)
4	Maximum Number of Connections	30
5	Duration	6,000 seconds
6	Routing Protocol	AODV
7	Packet Size	512 bytes
8	Packet Rate	4 packets/second
9	Maximum Speed	10 m/s
10	Pause Time	0–5 seconds
11	Mobility Models	RWP, RPGM, GM

Simulation 3: Comparative Performance Evaluation

Simulation 3 compared Real1 and Real2 under varying levels of node mobility and traffic loads using AODV and DSDV to identify protocol-specific strengths. Dynamic Source Routing (DSR) was considered but excluded due to persistent segmentation errors encountered in NS2.

Table 4 lists the parameters used in Simulation 3.

Table 4. *Parameters for Simulation 3.*

S/No.	Parameter Type	Parameter Value
1	Area	470 × 470 m²
2	Number of Nodes	30
3	Traffic Type	Constant Bit Rate (CBR)
4	Maximum Number of Connections	30
5	Duration	6,000 seconds
6	Routing Protocols	AODV, DSDV
7	Packet Size	512 bytes
8	Min/Max Packet Rate	4, 10 packets/second
9	Min/Max Speed	5 m/s, 10 m/s
10	Pause Time	0–5 seconds
11	Mobility Models	Real1 and Real2

Performance Metrics for Simulation 3

In addition to PDR and AEED, Normalized Routing Load (NRL) was computed to quantify routing overhead (Razouqi et al., 2024). NRL is defined as the ratio of total routing control packets transmitted to the total data packets successfully received at the destination. Lower NRL values indicate more efficient routing behaviour under mobility and traffic dynamics.

Simulation Platform: Network Simulator 2

For Simulation 3, all simulations were implemented using NS2. NS2 supports both wired and wireless networks, including MANETs, and provides modules for transport protocols (TCP, UDP), routing protocols (AODV, DSDV, DSR, TORA), and traffic generators (CBR, TELNET). NS2 operates on C++ (core) and OTcl (scripting).

TraceGraph Analysis

Simulation trace files were analysed using TraceGraph, a post-processing tool compatible with NS2 output formats (Alkenani & Nassar, 2022). TraceGraph supports more than 200 2D plots and 12 3D plots for metrics such as delay, jitter, round-trip time, and throughput. Although computation for 30-node scenarios can take up to an hour, the tool's graphical clarity and breadth of metrics make it suitable for MANET analysis.

Enhancing Credibility of Simulation Results

To enhance credibility and reproducibility of results in line with recommended practices (Hill, 2022), the following steps were applied:

- Verified TCL scripts for correct parameters.
- Validated Java post-processing code for formula accuracy.
- Examined AODV and DSDV trace formats and aligned metric computations accordingly.
- Executed 40 runs per scenario to approximate steady-state means.
- Discarded the initial 2,000 seconds of data to remove transient effects documented for models such as RWP.
- Computed 95% confidence intervals to quantify statistical reliability.

Traffic Source and Protocol Selection

Constant Bit Rate (CBR) traffic was selected to provide a time-invariant packet generation process for fair comparison across models and protocols. UDP was preferred over TCP due to lower control overhead, better performance under frequent path breakages, and reduced latency in highly dynamic MANET topologies.

ANALYSIS, INTERPRETATION AND JUSTIFICATION OF SIMULATION RESULTS

This section presents and interprets the results obtained from the three sets of simulations. Graphical illustrations, tables, and corresponding analyses are discussed to evaluate the behaviour and performance of the proposed models in comparison with existing ones.

Presentation and Analysis of Simulation 1 Results

The first set of simulations compared the proposed model (Real1) with Random Waypoint (RWP), Manhattan Grid (MG), and Gauss–Markov (GM) models. The analysis focused on key performance indicators including relative mobility, average number of partitions, average node degree, total number of links, and average link duration.

Relative Mobility

Relative mobility measures the average velocity of a node as a vector sum (Sirmollo & Bitew, 2021). Figure 16 illustrates that Real1 exhibits higher relative mobility across all transmission ranges compared to the other models.

This suggests that nodes in Real1 generally move toward destinations located farther apart, leading to improved communication efficiency in large-scale MANET operations. The clustering effect observed in RWP and RPGM models, where nodes tend to converge at the centre of the simulation area over time, reduces node-to-node distance, hence decreasing mobility. In contrast, Real1's higher mobility makes it more suitable for long-distance communication, as data packets reach destinations faster than in RWP, GM, or MG configurations.

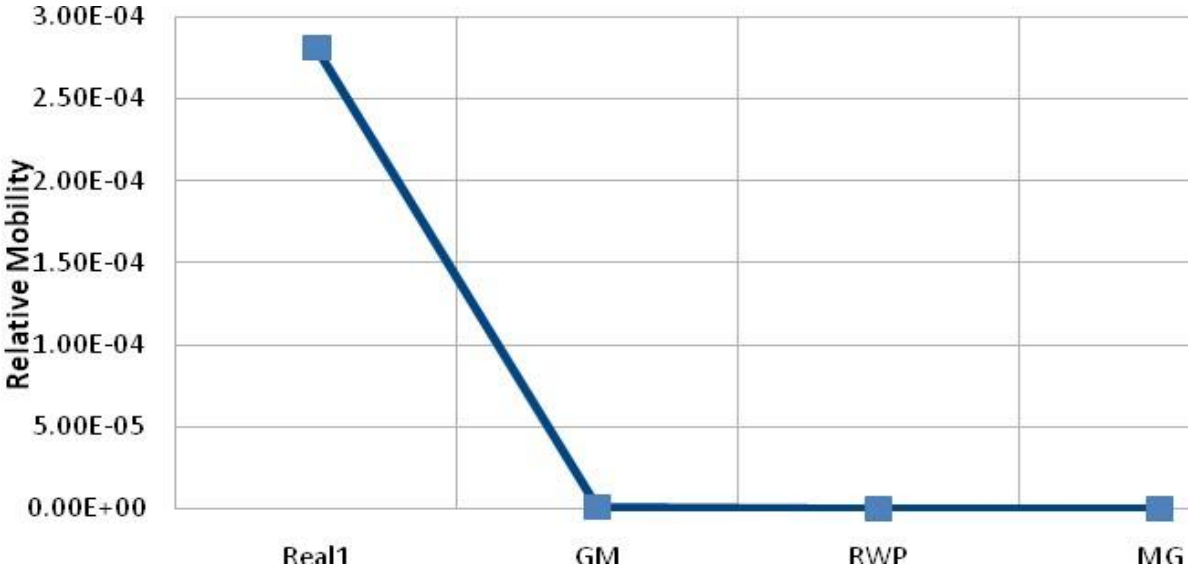


Figure 16. Comparison of Relative Mobility

Average Number of Partitions

The average number of partitions indicates how well-connected nodes remain within the network. At low transmission ranges, all models show higher partition counts due to reduced connectivity between distant nodes. As transmission range increases, connectivity improves and partitions decrease. For ranges between 0 m and 150 m, GM shows the highest number of partitions, consistent with its highly random movement patterns and frequent link breakages. Real1 and MG exhibit similar behaviour, while RWP demonstrates slightly better connectivity. Beyond 150 m, all models converge, though Real1 maintains a marginally lower partition count, indicating greater network cohesion at higher transmission ranges.

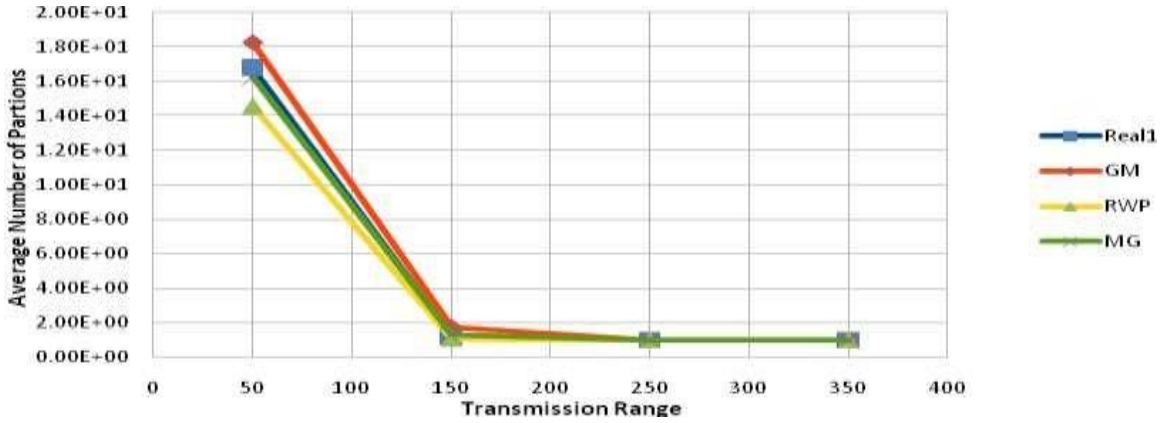


Figure 17. Comparison of Average Number of Partitions.

Average Node Degree

The average node degree represents the number of neighbour nodes each node can directly communicate with (Iskandarani, 2022). Two nodes are considered neighbours if they are within each other's transmission range. As shown in Figure 18, RWP achieves the highest node degree due to node clustering near the simulation centre. Real1 performs slightly better than the remaining models across transmission ranges of 100 m to 350 m, with the difference widening at higher ranges, confirming its improved link density and communication efficiency.

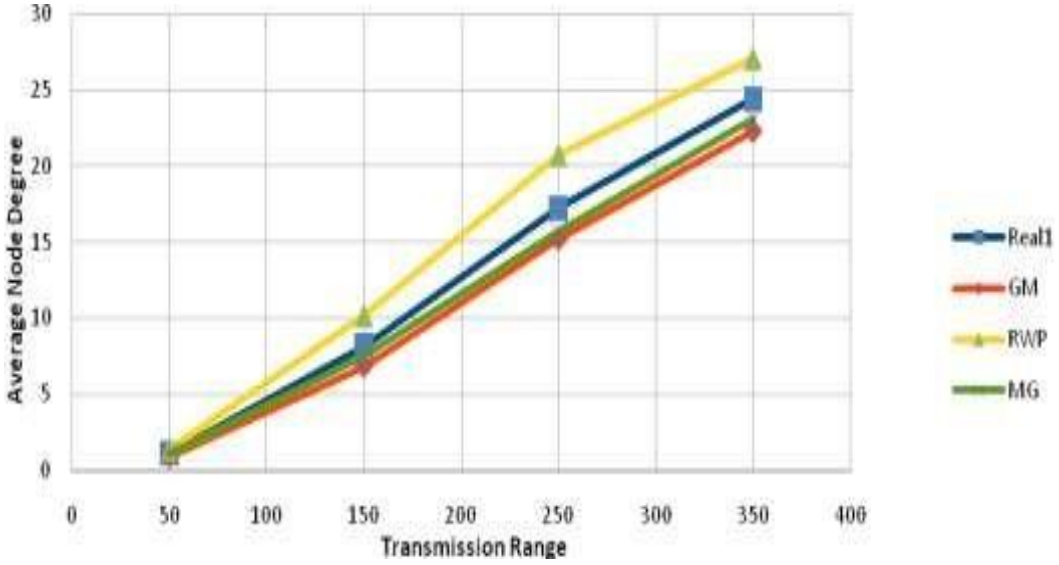


Figure 18. Comparison of Average Node Degree.

Total Number of Links

Links are created when two nodes move within transmission range and are broken when they move apart. As Figure 19 shows, the total number of links rises with transmission range up to 150 m across all models, although the rate of increase varies. Real1 consistently demonstrates the highest number of links at all ranges because it integrates multiple mobility patterns.

Manhattan Grid shows the lowest number of links, reflecting its constrained, path-based movement pattern. Beyond 250 m, link counts decline for all models except MG, likely due to reduced hop counts as range increases. Overall, Real1 sustains the best connectivity across scenarios.

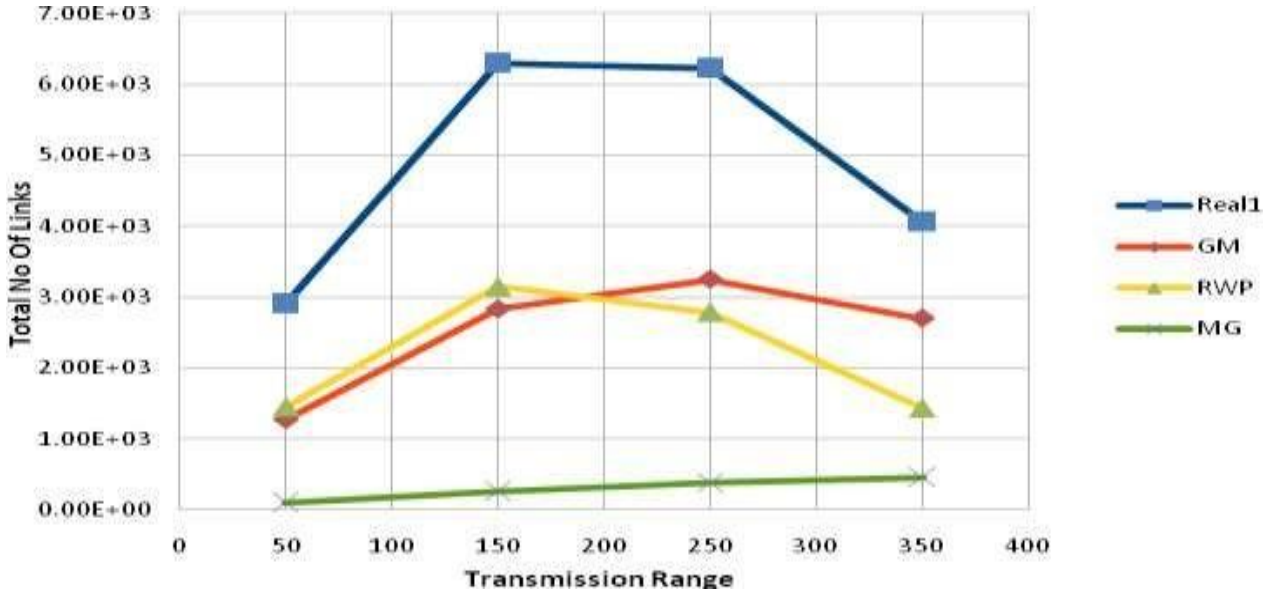


Figure 19. *Comparison of Total Number of Links.*

Average Link Duration

Figure 20 compares average link duration across all models. While Manhattan Grid creates fewer links, its structured movement produces the highest link duration, implying greater stability. Real1 and RWP maintain moderate durations, reflecting balanced mobility and reliability. Conversely, GM records the lowest link duration, reaffirming its high randomness and frequent link breaks.

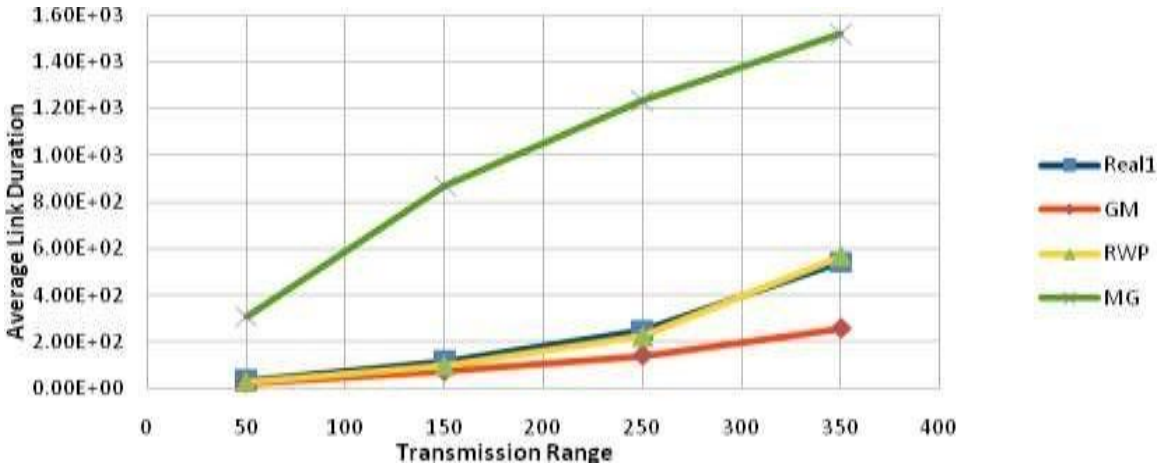


Figure 20. Comparison of Average Link Duration.

Performance Comparison of Simulation 1 Models

The performance ranking of Real1, GM, RWP, and MG is summarised in Table 5. The asterisk (*) indicates models with equivalent or overlapping performance.

Table 5: *Performance Rating of Real1, GM, RWP, and MG.*

Mobility Model	Relative Mobility	Average Link Duration	Total Number of Links	Average Node Degree
Real1	1	2*	1	2
GM	2*	4	2*	4
RWP	2*	3*	3*	1
MG	2*	1	4	3

It can be inferred from Table 5 that Real1 achieved the best overall performance, ranking first or second across all evaluated metrics.

Presentation and Analysis of Simulation 2 Results

Following the success of Simulation 1, Simulation 2 examined the performance of Real1 and Real2, alongside other models.

Generated and Sent Packets

Gauss–Markov generated the highest number of packets but transmitted roughly the same number as Real1,

Real2, and RWP. RPGM produced and sent the fewest packets, while MG showed intermediate results, close to Real2 and RWP but with slightly reduced transmission counts.

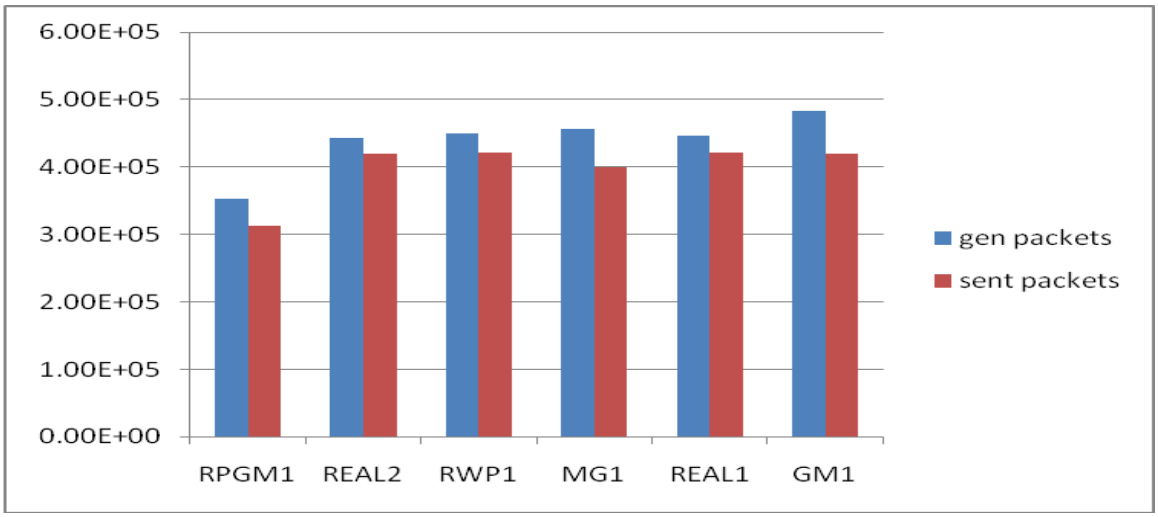


Figure 21. *Comparison of Generated and Sent Packets*

Forwarded, Dropped, and Lost Packets

Although GM generated the most packets (Figure 22), it also experienced the highest packet losses alongside MG. GM's behaviour aligns with its randomness, but MG's results are unexpected given its long link durations (Figure 20). Real1 and Real2 exhibited similar patterns for forwarded and lost packets, while RPGM achieved the lowest overall values for all packet metrics, consistent with its limited generation and transmission rates.

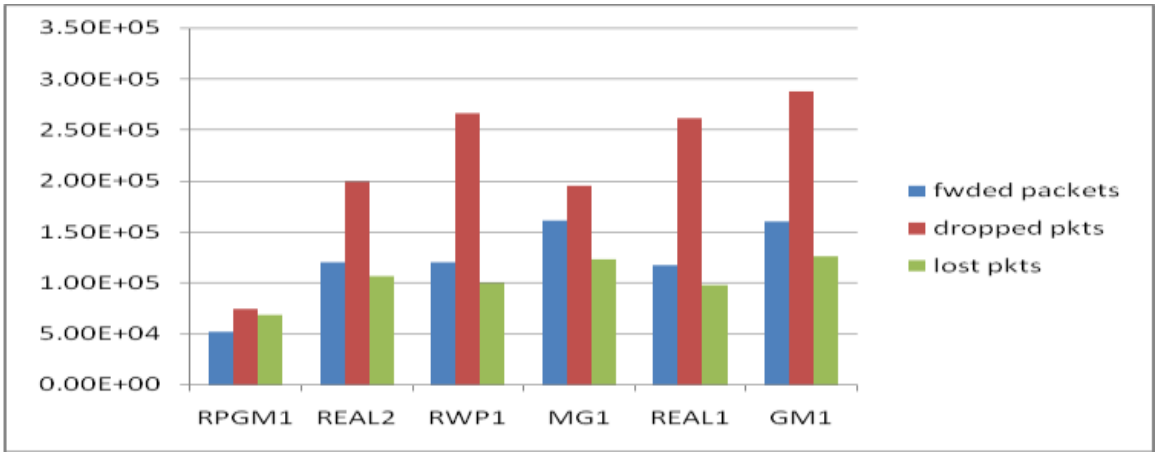


Figure 22. *Comparison of Forwarded, Dropped, and Lost Packets*

Average End-to-End Delay and Normalised Routing Load

As shown in Figure 23, GM demonstrates the highest Average End-to-End Delay (AEED). Nevertheless, all models show AEED values below 50 ms, confirming their suitability for real-time communication. GM also records the highest Normalised Routing Load (NRL),

while Real1 and Real2 exhibit lower, nearly identical NRLs.

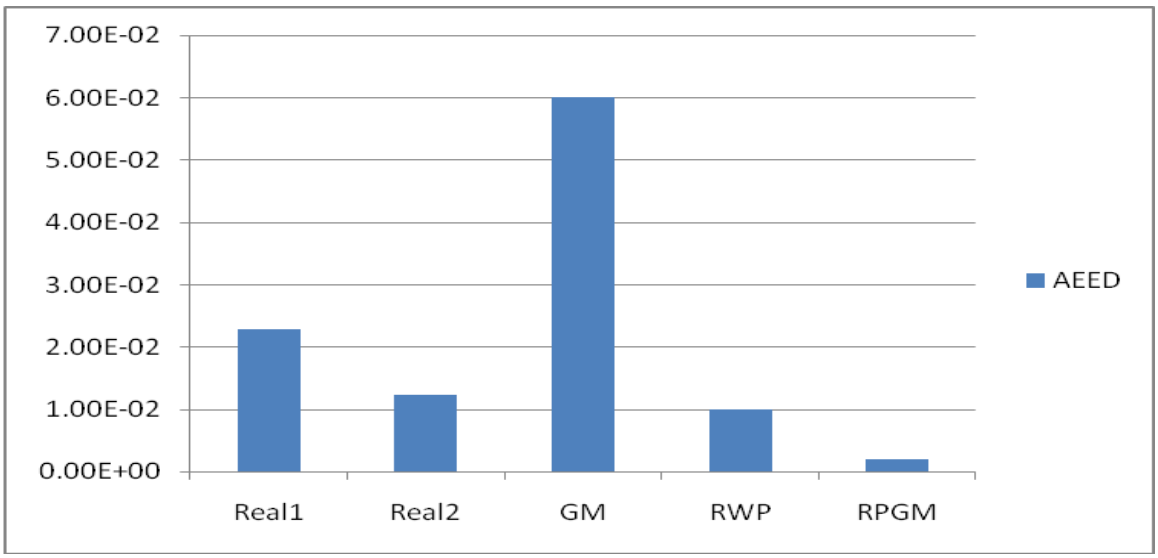


Figure 23. *Comparison of Average End-to-End Delay*

Table 6 gives the numerical values of all the mobility models obtained from simulation.

Table 6: *Numerical Values of AEED for All Mobility Models*

Model	Real1	Real2	GM	RWP	RPGM
AEED (s)	2.29E-02	1.24E-02	6.00E-02	1.00E-02	1.92E-03

RPGM achieved the highest Packet Delivery Ratio (PDR), followed by RWP and Real2, largely due to

robust intra-group and inter-group communication. GM again showed the weakest performance, losing and dropping the most packets.

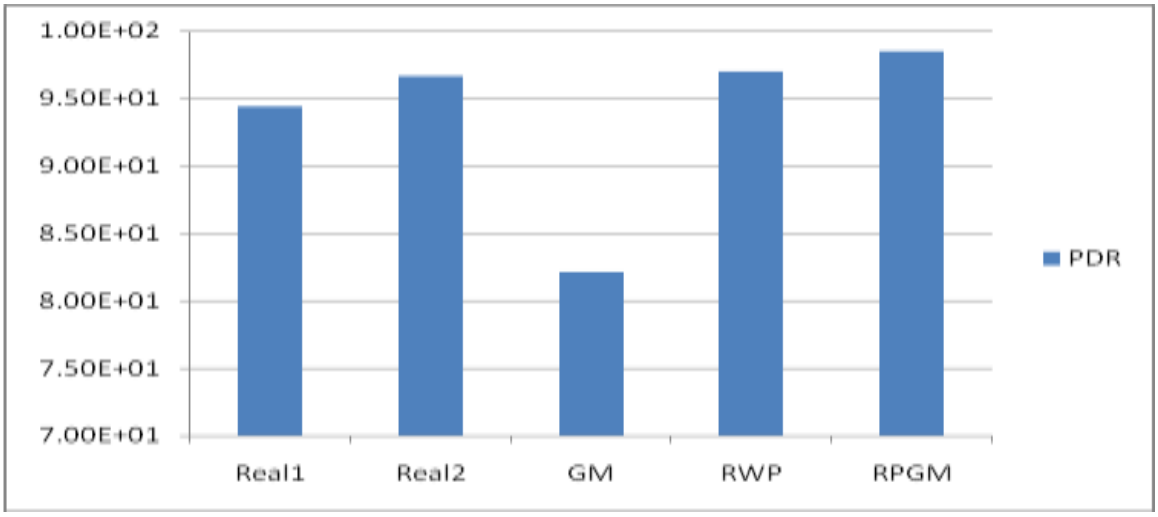


Figure 24. Comparison of Packet Delivery Ratio

Throughput-versus-delay graphs (Figures 25–30) show that Real1 and Real2 both demonstrate minimal delay variation, indicating high stability. Real2 performs slightly better overall, suggesting its hybrid entity–group structure more accurately represents realistic SAR mobility.

Figures 25–30: *Throughput of Receiving Bits vs. Average End-to-End Delay (GM, RWP, Real1, MG, RPGM, Real2).*

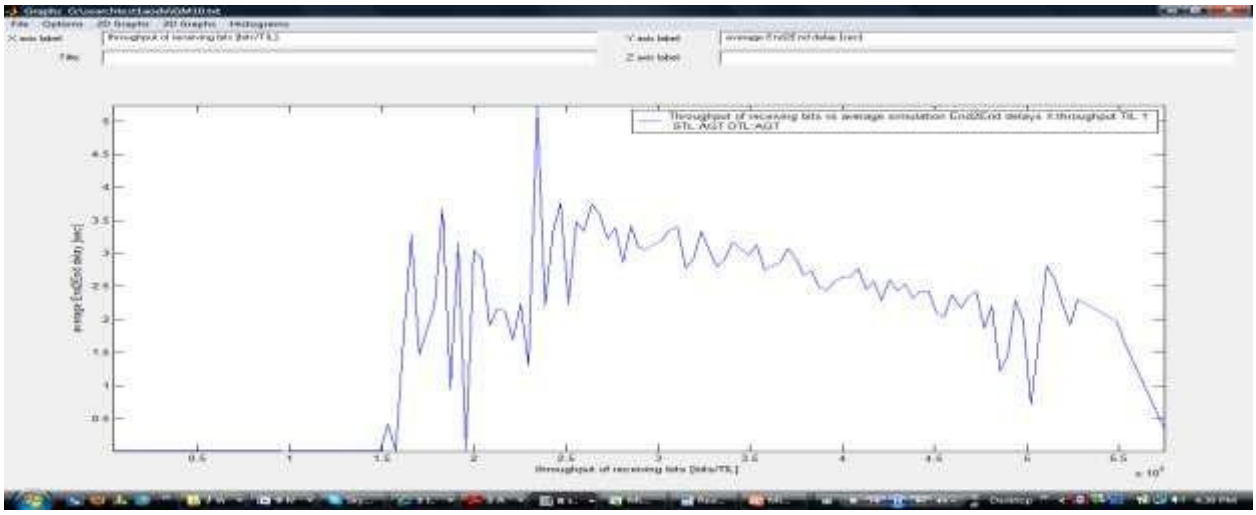


Figure 25. *Throughput of receiving bits versus average end-to-end delay for GM*

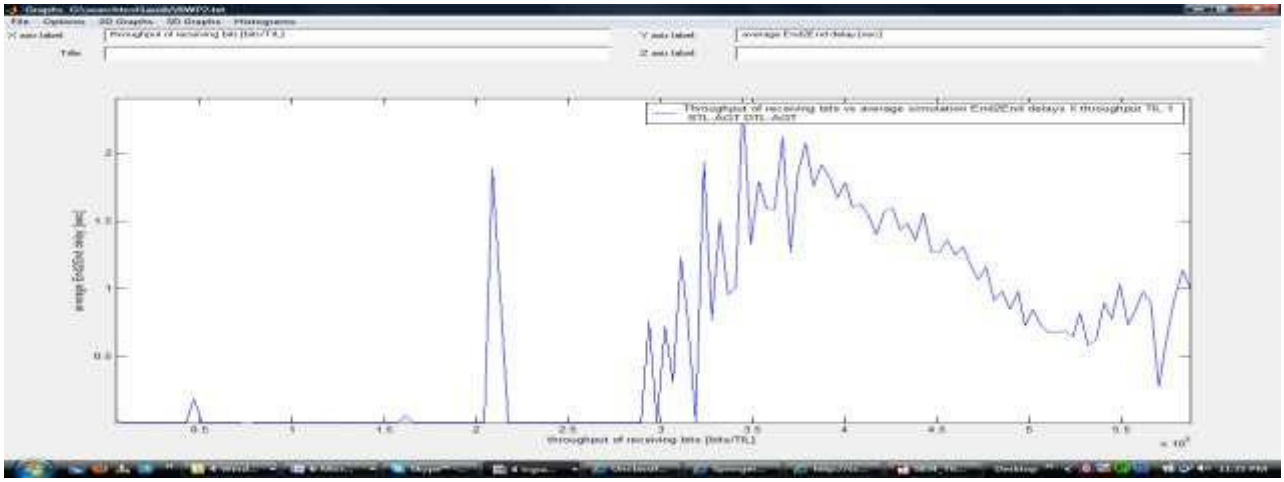


Figure 26. Throughput of receiving bits versus average end-to-end delay for RWP

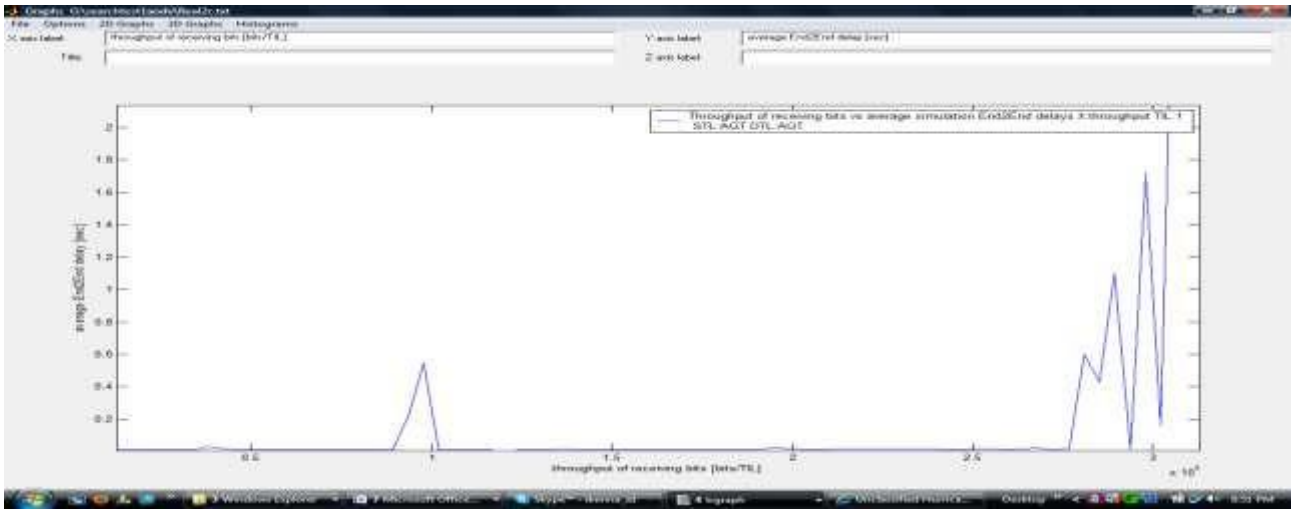


Figure 27. *Throughput of receiving bits versus average end-to-end delay for Real1*

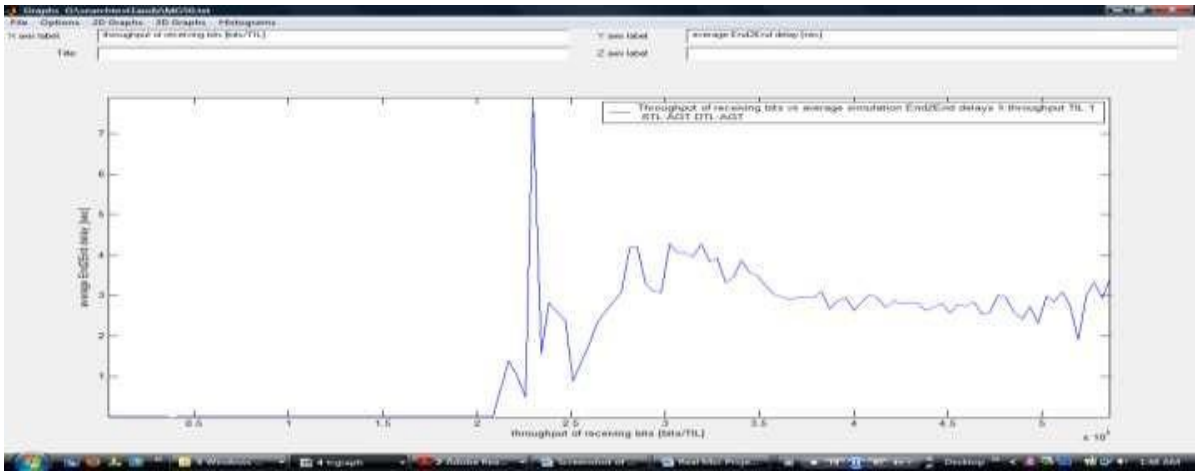


Figure 28. *Throughput of receiving bits versus average end-to-end delay for MG*

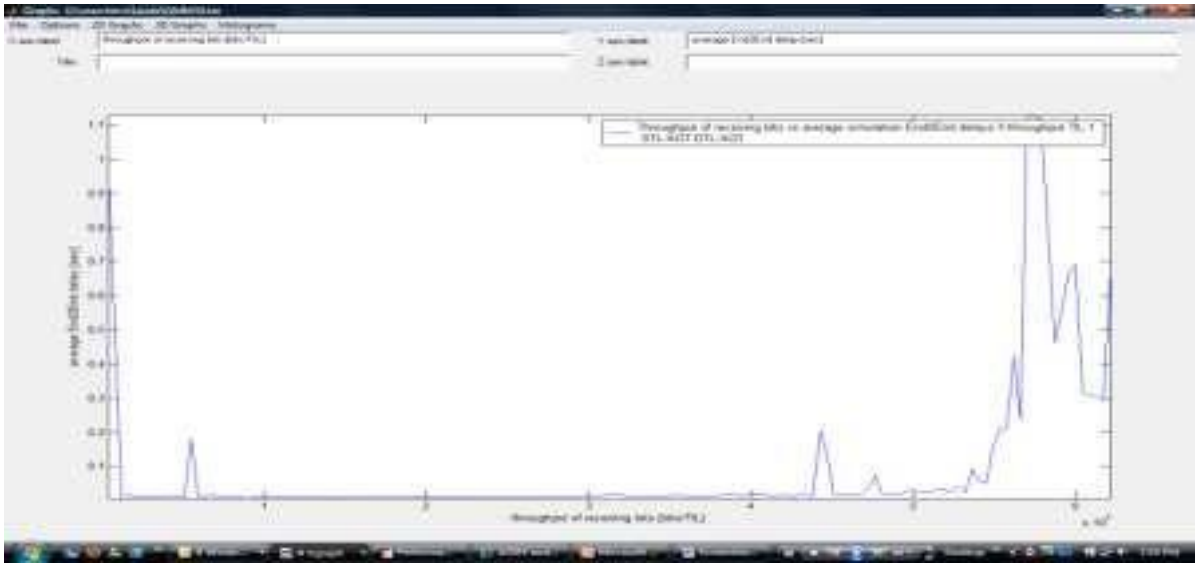


Figure 29. *Throughput of receiving bits versus average end-to-end delay for RPGM*



Figure 30. *Throughput of receiving bits versus average end-to-end delay for Real2*

Performance Comparison Between Real1 and Real2

Table 7 compares Real1 and Real2 using the same metrics.

Table 7. *Comparison of Real1 and Real2*

Metric	Forwarded Packets	Lost Packets	AEED	NRL	PDR	Throughput	Avg. Delay
Real1 Position	2	1	2	2	2	2	2
Real2 Position	1	2	1	1	1	1	1

Overall, Real2 outperformed Real1, particularly in AEED, NRL, and PDR, confirming its superior mobility representation.

Presentation and Analysis of Simulation 3 Results

The third simulation compared Real1 and Real2 under varying node mobility and traffic load conditions, using both AODV and DSDV routing protocols.

Packet Delivery Ratio (PDR)

Figures 31 and 32 illustrate that Real1 and Real2 maintain similar PDRs, though Real2's values are marginally higher. High mobility and heavy traffic significantly affect MANET topology, leading to frequent link breakages. AODV consistently outperformed DSDV, especially under high-mobility, high-traffic conditions. This aligns with findings by Ayidu & Elaigwu (2022), Ali et al. (2023) and Ghazali et al. (2024), which recommend AODV as the preferred protocol for real-time voice communication under UDP.

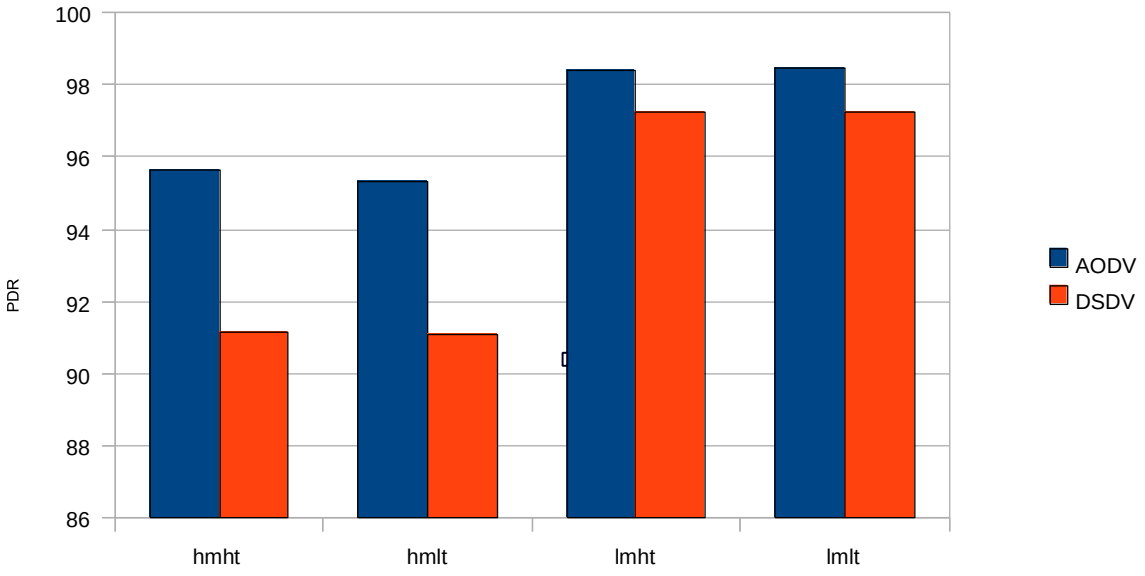


Figure 31. *PDR of Real2 Using AODV and DSDV Under Different Mobility and Traffic Loads*

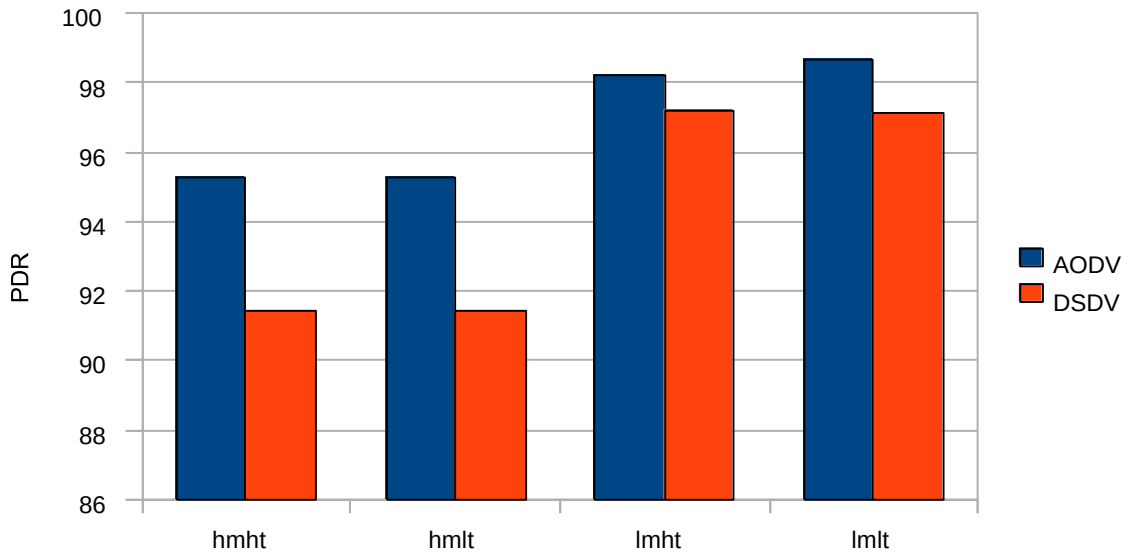


Figure 32. *PDR of Real1 Using AODV and DSDV Under Different Mobility and Traffic Loads*

Normalised Routing Load (NRL)

NRL results (Figures 33 and 34) show that both Real1 and Real2 exhibit similar trends. NRL remains higher for AODV under heavy traffic, as the protocol relies on frequent route discovery floods, increasing control overhead. These findings reaffirm that while AODV is more adaptive, it incurs higher routing costs compared to DSDV, particularly in dense or dynamic networks.

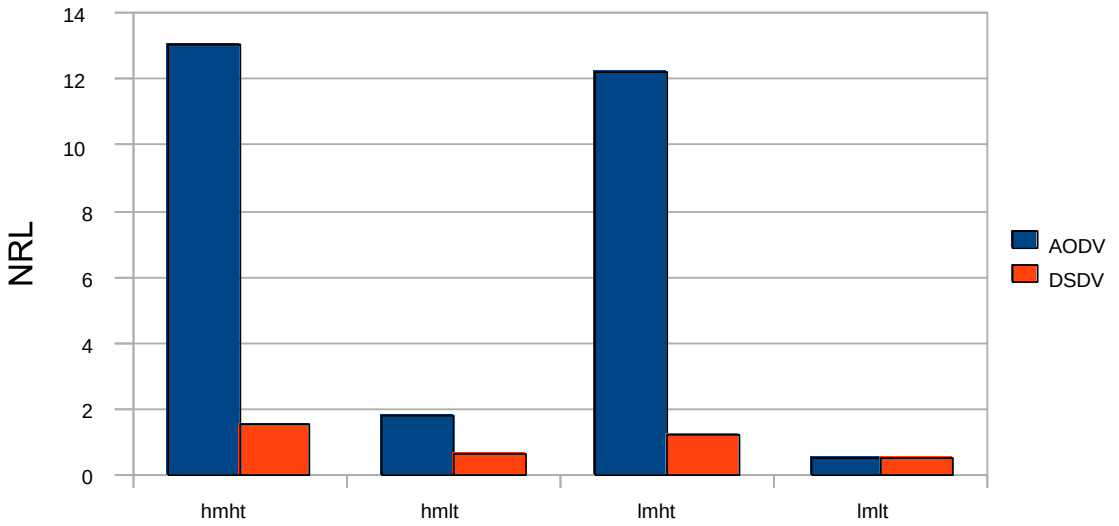


Figure 33. NRL of Real2 Using AODV and DSDV Under Different Mobility and Traffic Loads

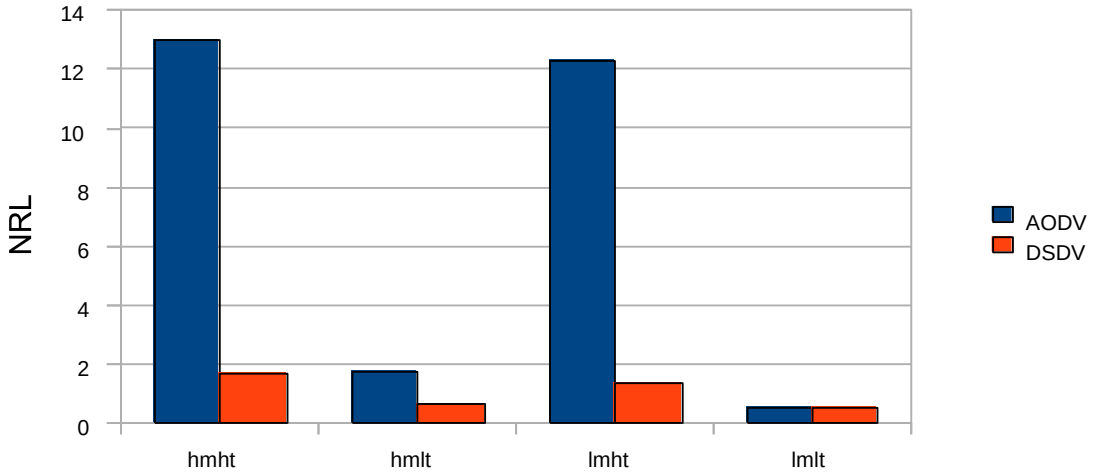


Figure 34. *NRL of Real1 Using AODV and DSDV Under Different Mobility and Traffic Loads*

LIMITATIONS

This study faced several noteworthy limitations that should be acknowledged. First, there is a paucity of existing research focusing on mobility modelling in disaster scenarios. Most previous studies have primarily examined military applications of MANETs, leaving a significant gap in the literature concerning civilian search-and-rescue contexts. Consequently, identifying comparable empirical works proved challenging.

In addition, while many related studies clearly described their methodologies and justified their findings, few reported the empirical or numerical results of their simulations. This lack of quantitative benchmarks limited opportunities for

direct comparison and external validation of the present findings.

Nevertheless, the majority of results obtained in this study align closely with established theoretical expectations, which supports their validity and consistency with existing MANET behaviour. A few outcomes, however, diverged slightly from theoretical predictions or lacked sufficient precedent in prior literature. These anomalies have been carefully documented and are recommended as promising avenues for further investigation.

DIRECTIONS FOR FUTURE RESEARCH

Several opportunities exist to extend and deepen the findings of this study. One immediate avenue for future research is to investigate the performance of the proposed mobility models using alternative routing protocols such as Dynamic Source Routing (DSR) and hybrid protocols (e.g., ZRP and TORA). These protocols exhibit distinct mechanisms for route discovery and maintenance, and their evaluation under the proposed models could reveal more nuanced insights into routing efficiency, overhead management, and link stability across diverse network conditions.

Beyond routing protocols, future studies could expand the experimental parameters of the current work. This includes varying node density, simulation area, and traffic load to assess how scalability and congestion affect network performance. Incorporating realistic traffic patterns, such as multimedia or real-time data streams, could also enhance understanding of the models' suitability for latency-sensitive applications like emergency communication, telemedicine, and disaster coordination systems.

Another promising direction involves introducing environmental factors such as obstacles, signal attenuation, or interference, which were simplified or excluded in the present study. Integrating these spatial constraints could yield more realistic simulations of post-disaster landscapes where communication is often hindered by debris, damaged infrastructure, and irregular terrain.

Additionally, the methodology could be extended through multi-scenario validation. Applying the models to different operational contexts, such as urban emergency response, wildfire management, or humanitarian relief missions, would help determine the adaptability and generalisability of the proposed approach. Comparative studies across these domains could also highlight how mobility dynamics vary with geographical, infrastructural, and social factors.

In the longer term, future work may explore machine learning–based optimisation of mobility parameters. Leveraging predictive algorithms could enable dynamic adjustment of node movement or routing behaviour in real time, improving network resilience and efficiency under unpredictable conditions. Similarly, integrating the proposed mobility framework into next-generation wireless systems, such as 5G and 6G-enabled ad hoc networks or Internet of Things (IoT)–driven emergency infrastructures, would provide a natural extension of this research into emerging communication paradigms.

Finally, collaboration between computer scientists, emergency planners, and communication engineers could support the development of simulation testbeds or field deployments. Such interdisciplinary work would bridge the gap between theoretical modelling and real-world disaster management, ensuring that the insights gained from this study translate into practical tools for saving lives and improving communication reliability in crisis situations.

CONCLUSION

This research proposed a new mobility model specifically designed to capture the unique movement patterns of Search-and-Rescue (SAR) teams operating in disaster scenarios. The model was developed by integrating the characteristics of both entity and group mobility frameworks, based on the premise that the behaviour of responders in such environments inherently combines individual and collective movement dynamics.

The results of the simulations demonstrated the feasibility of merging existing entity and group mobility models into a unified framework. Comparative analyses revealed that the new models performed consistently well across multiple performance metrics when evaluated against their constituent models. Among the proposed designs, Real2 achieved

the highest overall performance and is therefore recommended as the representative model for disaster-oriented MANET simulations.

Beyond confirming the viability of the proposed approach, the findings underscore the central role of mobility in determining MANET performance. The results show that routing efficiency, connectivity, and stability are all significantly influenced by the accuracy with which node mobility is represented. Consequently, when evaluating the performance of MANET routing protocols in any given environment, it is essential that the underlying mobility model authentically reflects the real-world movement behaviours present in that scenario.

Thus, this work contributes both conceptually and practically to the field of mobile ad hoc network research. It not only advances understanding of mobility modelling in disaster contexts but also provides a methodological foundation for developing more realistic, adaptable, and effective MANET frameworks for emergency response 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 I.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 F.I. 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.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

ACKNOWLEDGEMENT

The authors acknowledge the management and technical staff of PENKUP Research Institute, Birmingham, UK, for their excellent assistance and for providing medical writing and editorial support in accordance with the Good Publication Practice (GPP3) guidelines.

References

1. Ahmed, B., Moeyaert, V. and Mégret, P., (2025). Latency Characterization and Performance Evaluation of Synchronized Daisy-Chain EtherCAT Networks Using Standard Cable Pairs and Open-Source Master Solutions. *IEEE Transactions on Network and Service Management*.

2. Ajere, I. U., Obohwemu, K. O., Emeka, C., Akabuokwu, K. C., Ooju, O. E., Akadiri, M. O., ... & Sogra, S. F. (2026). A Realistic Hybrid Mobility Model for Search-and-Rescue Teams in Mobile Ad Hoc Networks. *International Research Journal of Advanced Engineering and Technology*, *3*(01), 06-14.

3. Al-Allaq, Z.J., Shakir, W.M. and Charafeddine, J., (2025). A Comprehensive Review of Cutting-Edge Disaster Response: UAVs Equipped with FSO-Based Communications. *Wireless Personal Communications*, pp.1-66.

4. Ali, A.M., Ngadi, M.A., Al_Barazanchi, I.I. and JosephNg, P.S., (2023). Intelligent traffic model for unmanned ground vehicles based on DSDV-AODV protocol. Sensors, 23(14), p.6426.

5. Alkenani, J. and Nassar, K.A., (2022). Enhanced system for ns2 trace file analysis with network performance evaluation. *Iraqi J. Intell. Comput. Informatics*, *1*(2), pp.119-130.

6. Alsayyed, M.M., Manickam, S., Wulandari, E.R.N., Widia, I.D.M. and Karuppayah, S., (2025). A Review of Applicable Technologies, Routing Protocols, Requirements, and Architecture for Disaster Area Networks. *IEEE Access*.

7. Ammar, H.A., Adve, R., Shahbazpanahi, S., Boudreau, G. and Srinivas, K.V., (2021). RWP+: A new random waypoint model for high-speed mobility. *IEEE Communications Letters*, *25*(11), pp.3748-3752.

8. Ansari, J.A., Ishak, M.K. and Ammar, K., (2025). Combined Architecture of Destination Sequence Distance Vector (DSDV) Routing with Software Defined Networking (SDN) and Blockchain in Cyber-Physical Systems. *Computers, Materials & Continua*, *82*(2).

9. Ayidu, N.J. and Elaigwu, V.O., (2022). Probability model for User Datagram Protocol (UDP) upstream throughput for single user in real time and non-real time scenarios in IEEE802.11b/g WLAN. NIPES-Journal of Science and Technology Research, 10: 4(2).

10. Eltahlawy, A.M., Aslan, H.K., Abdallah, E.G., Elsayed, M.S., Jurcut, A.D. and Azer, M.A., (2023). A survey on parameters affecting MANET performance. *Electronics*, *12*(9), p.1956.

11. Ghazali, F., Anwar, N.F., Gunasegaran, S., Aminordin, A.N., Rafie, M.H., Izham, A.I., Mazlan, M.A., Mahiddin, N.A. and Zakaria, Z.A., (2024). Unveiling the performance of AODV, OLSR, and DSR in flying ad hoc networks. Malaysian Journal of Computing and Applied Mathematics, 7(2), pp.45–57.

12. Hill, D.R., (2022), October. Reproducibility of simulations and high performance computing. In *ESM 2022, European Simulation and Modelling Conference* (pp. 5-9).

13. Iskandarani, M.Z., (2022). Effect of number of nodes and distance between communicating nodes on WSN characteristics. *environments*, *1*, p.6.

14. Jindal, R., Tripathi, A., Kaur, H. and Sharma, S., (2025). Integrating AI, Robotics, and Augmented Reality in Disaster Management. In *Addressing Environmental Challenges With AI, Robotics, and Augmented Reality* (pp. 289-324). IGI Global Scientific Publishing.

15. Kagai, F., Branch, P., But, J., Allen, R. and Rice, M., (2024). Rapidly deployable satellite-based emergency communications infrastructure. *IEEE Access*.

16. Karaman, B., Basturk, I., Taskin, S., Zeydan, E., Kara, F., Beyazıt, E.A., Camelo, M., Björnson, E. and Yanikomeroglu, H., (2025). Solutions for sustainable and resilient communication infrastructure in disaster relief and management scenarios. *IEEE Communications Surveys & Tutorials*.

17. Kour, S. and Singh, J., (2022). Performance evaluation of enhanced manhattan mobility model over GM, RWP, Manhattan Grid, SLAW, and TLW mobility models in MANETs. *Recent Advances in Computer Science and Communications (Formerly: Recent Patents on Computer Science)*, *15*(7), pp.992-1000.

18. Mabina, A., (2025). Mobile Ad Hoc Network (MANET) Performance in Disaster Recovery. *International Journal of Artificial Intelligence and Science*, *2*(2), pp.105-123.

19. Mahiddin, N.A., Affandi, F.F.M. and Mohamad, Z., (2021). A review on mobility models in disaster area scenario. *International Journal of Advanced Technology and Engineering Exploration*, *8*(80), pp.848-873.

20. Matracia, M., Saeed, N., Kishk, M.A. and Alouini, M.S., (2022). Post-disaster communications: Enabling technologies, architectures, and open challenges. *IEEE Open Journal of the Communications Society*, *3*,

pp.1177-1205.

21. Mohamed, S.M., Hamza, H.S. and Saroit, I.A., (2017). Coverage in mobile wireless sensor networks (M-WSN): A survey. *Computer Communications*, *110*, pp.133-150.

22. Pasandideh, F., da Costa, J.P.J., Kunst, R., Islam, N., Hardjawana, W. and Pignaton de Freitas, E., (2022). A review of flying ad hoc networks: Key characteristics, applications, and wireless technologies. *Remote Sensing*, *14*(18), p.4459.

23. Rahman, M.T., Alauddin, M., Dey, U.K. and Sadi, S., (2023). Adaptive, secure and efficient routing protocol to enhance the performance of Mobile Ad Hoc Network (MANET). *Applied Computer Science*, *19*(3).

24. Ramphull, D., Mungur, A., Armoogum, S. and Pudaruth, S., (2021), May. A review of mobile ad hoc NETwork (MANET) Protocols and their Applications. In *2021 5th international conference on intelligent computing and control systems (ICICCS)* (pp. 204-211). IEEE.

25. Razouqi, Q., Boushehri, A., Gaballa, M., Alsaleh, L. and Abbod, M., (2024). Extended comparison and performance analysis for mobile Ad-Hoc networks routing protocols based on different traffic load patterns and performance metrics. *Electronics*, *13*(14), p.2877.

26. Reddy, B. and Dhananjaya, B., (2022). The AODV routing protocol with built-in security to counter blackhole attack in MANET. *Materials Today: Proceedings*, *50*, pp.1152-1158.

27. Robertson, E.C., (2025). Weathering the Storm: Examining Mississippi's Disaster Recovery for Diverse Economic Groups.

28. Scatà, M., (2025). *The Power of Complex Systems: Unlocking Intelligence in Mobile Communication Networks*. Springer Nature.

29. Singh, M., Jhajj, N.K. and Goraya, A., (2022). IoT-enabled wireless mobile ad-hoc networks: introduction, challenges, applications: review chapter. *Internet of Things*, pp.121-134.

30. Sirmollo, C.Z. and Bitew, M.A., (2021). Mobility-Aware Routing Algorithm for Mobile Ad Hoc Networks. *Wireless Communications and Mobile Computing*, *2021*(1), p.6672297.

31. Smera, C. and Sandeep, J., (2022), October. Networks simulation: Research based implementation using tools and approaches. In *2022 IEEE 3rd Global Conference for Advancement in Technology (GCAT)* (pp. 1-7). IEEE.

32. Whatley, C., (2023). *A High-Resolution Hurricane Analysis for the Southeastern United States* (Master's thesis, Auburn University).

33. Wilson, K., Bibby, D., Halford, C. and Galloway, A., (2023). Deployment Strategies for SAR/USAR Teams. In *The Path of Flames* (pp. 158-178). CRC Press.

34. Zhang, T., Liu, H., Guo, Z., Xia, D., Kong, L., Zhang, X., Wang, T. and Wang, Y., (2025). Navigating the Complex Landscape of Emergency Rescue: Insights from a Co-Citation Analysis. *Current Science*, *5*(2), pp.1787-1805