A Dynamic Simulation Framework for Mobile Ad Hoc Networks in Search and Rescue Operations

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Abstract

Network simulation is a cost-effective, widely adopted method for testing and improving new protocols and solutions in Mobile Ad Hoc Networks (MANETs). Despite the prevalence of simulation-based studies, the absence of unified, extensible frameworks limits the modelling of end-to-end communication and the generation of reusable datasets necessary for research reproducibility. Our paper introduces a simulation framework for evaluating MANETs in Search and Rescue (SAR) scenarios, developed entirely in NS-3 to streamline both simulation and dataset generation. The framework incorporates mobility modelling, energy tracking, communication dynamics, and quality of service (QoS) logging within a modular architecture. It implements heterogeneous nodes with role-specific behaviours and supports discovery mechanisms such as line-of-sight, beacon broadcasting, and signal-based detection. Two simulation versions are implemented using different propagation loss models to assess performance under ideal and obstructed conditions. Routing protocols, including AODV, OLSR, and DSDV, are evaluated across varying scalability levels. Our results confirm established trends in MANET routing and demonstrate the framework's flexibility in simulating mission-driven environments. The work presents multiple datasets and a reusable, extensible, scenario-driven simulation environment for researchers investigating MANET behaviour in complex applications such as disaster

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relief and tactical communications.

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1. Introduction

The use of simulation tools in communication networks has revolutionised the way researchers study and develop new network architectures. Researchers can adapt these tools to model various network setups, protocols, and scenarios, which is a crucial step when exploring and evaluating novel algorithms [1].

These simulation capabilities have proven particularly valuable in the domain of MANETs, where research has grown significantly in the recent decade, with various studies focusing on protocol optimisation [2, 3], energy balancing [4, 5, 6], security and resilience [7, 8, 9], and performance enhancements [10]. These networks are essential for mission-critical operations such as SAR, where the efficacy of communication protocols constitutes an important factor in determining mission outcomes with life-saving implications.

SAR operations often occur in challenging environments with dynamic mobility patterns, where teams must coordinate and adapt to unpredictable changes in terrain, obstacles, and environmental conditions.

Previous studies on MANETs in disaster management have made valuable contributions, but a large portion focuses on building systems rather than developing and evaluating simulation frameworks. For example, Meissner et al. [11] designed a layered communication system using satellite and terrestrial technologies to support emergency coordination. Similarly, Mecella et al. [12] introduced a peer-to-peer infrastructure to help teams work together during emergencies and Catarci et al. [13] extended this with user-centred tools for field coordination. Jang et al. [14] built a rescue information platform (RISED) to support earthquake response, integrating features like route generation and resource tracking.

In contrast, some researchers have focused more on mobility modelling and simulations, although these studies are often limited in scope. Jang et al. [15] introduced a graph-based mobility model that uses real maps to simulate how people move in constrained environments. Bai et al. [16] introduced a realistic mobility model for mobile ad hoc networks that uses actual geographic maps to constrain node movement, offering a more practical alternative to random mobility models. Kim et al. [17] used trace data to build a more realistic picture of user mobility. These works improve how movement is represented, but they usually do not connect that with communication performance, routing behaviour, or rescue workflows.

A significant limitation present in both system-centric and simulation-oriented research studies is the assumption of optimal network conditions. Existing implementations frequently neglect to incorporate critical real-world variables, including weather changes (rain, fog, or snow), topographical variations, and energy resource constraints. Consequently, the generalisability of the findings does not scale well when applied to disaster response scenarios. MANETs simulations often fall short on at least one of these dimensions, limiting the applicability of the results in real-world SAR planning and response.

To address these limitations, our research proposes that simulation-based MANETs would be enhanced through the implementation of a comprehensive unified framework. Providing a modular platform for researchers studying adaptive MANETs protocols and emergency response network architectures. Our work presents a dynamic simulation framework[1] implemented using NS-3, employing SAR operations as a case study to validate our methodological approach.

Our primary research objective is to develop a framework architecture that is *dynamically adaptable*, allowing researchers to customise nodes, topologies, mobility patterns, as well as terrain and environmental obstacles, without requiring the reconstruction of the underlying implementation. A key feature of this framework is its ability to generate structured, customisable datasets that include mobility trajectories, SAR operations, energy utilisation, and network performance indicators. This functionality helps address the resource-intensive process of independently constructing and configuring testing scenarios, thereby reducing barriers to entry for MANETs research and facilitating reproducible protocol evaluation.

Our research has three main contributions to the domain of MANET-based simulation studies and emergency communications:

- *Core Framework Implementation:* The standalone core framework enables simulation of various node types and communication mechanisms. This baseline configuration facilitates testing of new routing protocols,

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[1] The framework code is available at: `https://github.com/ManalAGhanem/SAR-Framework`

energy models, and communication mechanisms within a controlled, scenario-independent environment.

- *Dynamic Scenario Architecture:* Built upon the core framework, the scenario layer introduces mission-specific logic through a modular structure. Using a SAR context as a proof-of-concept, we demonstrate how the framework can be extended to support discovery mechanisms.
- *Dynamic Dataset Generation:* The framework generates structurally coherent logs and datasets documenting node interactions and network performance parameters.

Through these contributions, our work bridges the gap between theoretical MANETs research and practical applications, thereby supporting the development and evaluation of robust communication protocols for deployment in challenging operational environments.

The rest of this paper is structured as follows. Section 2 provides the framework definitions, highlighting how each module is designed and how they interconnect. In Section 3 and Section 4, we detail the implementation within NS-3 and the experimental evaluations respectively. Section 5 discusses the dataset generation, followed by a discussion of the limitations in Section 6. Finally, Section 7 offers concluding remarks and proposes avenues for future work.

2. Framework Definition

In this section, we present the overall definition of our framework. We describe the creation and configuration of nodes, the communication structure, which may be generalised or tailored to a SAR context, as demonstrated below, quality of service configuration, the choice of the simulator and its parameters, and the scenario-specific implementation of SAR processes.

Figure 1 presents the framework abstraction, which is organised into two primary categories: Core Setup and Scenario Implementation. Both are dynamic and allow for changes, either to introduce new protocols in the core setup or to modify the specific mission processes and scenarios. The core setup of the framework is fully functional without the SAR-specific scenario implementation, where nodes send and receive different types of data (GPS, Voice, Video, Environment) and support various communication styles. The

SAR scenario in the framework adds a mission-specific application that can be expanded or adapted to fit other scenarios.

The proposed framework abstracts SAR operations at a functional level while remaining configurable to represent different real-world missions. For instance, post-disaster urban searches can be modelled using ground teams and vehicles operating under obstructed propagation conditions, whereas flood or wildfire scenarios can be represented through drone-led searches with limited ground mobility. Scenarios involving isolated or inaccessible terrain can similarly be captured by adjusting node roles, mobility constraints, and communication capabilities. By varying these parameters, the same framework can represent different SAR contexts without changing its core structure, enabling realistic yet controlled evaluation of MANETs behaviour. The following subsection details the described structure. Table 1 summaries the main framework modules and their roles.

Framework Layer	**Module**	**Role**
Core Setup	Network Configuration	Initialises nodes, wireless interfaces, IP addressing, and routing protocol selection
	Routing Layer	Integrates MANETs routing protocols (AODV, OLSR, DSDV) for comparative evaluation
	Communication Stack	Manages data, control, and application-level message exchanges between nodes
	Mobility Configuration	Defines baseline mobility models and node-specific speed and pause parameters
	Logging & Metrics	Collects network performance metrics (PDR, delay, jitter, throughput) and simulation logs
Scenario Implementation	SAR Node Roles	Defines SAR-specific entities (rescue teams, base station, civilians) and their capabilities
	Search & Discovery	Implements passive and active civilian discovery mechanisms
	Civilian Attachment & Rescue	Models reaching civilians, initiating rescue actions, and tracking civilian safety status
	Scenario Control	Configures scenario scale, node density, obstructions, and runtime behaviour
	Logging & Metrics	SAR-related logging

Table 1: Overview of Framework Modules and Their Roles

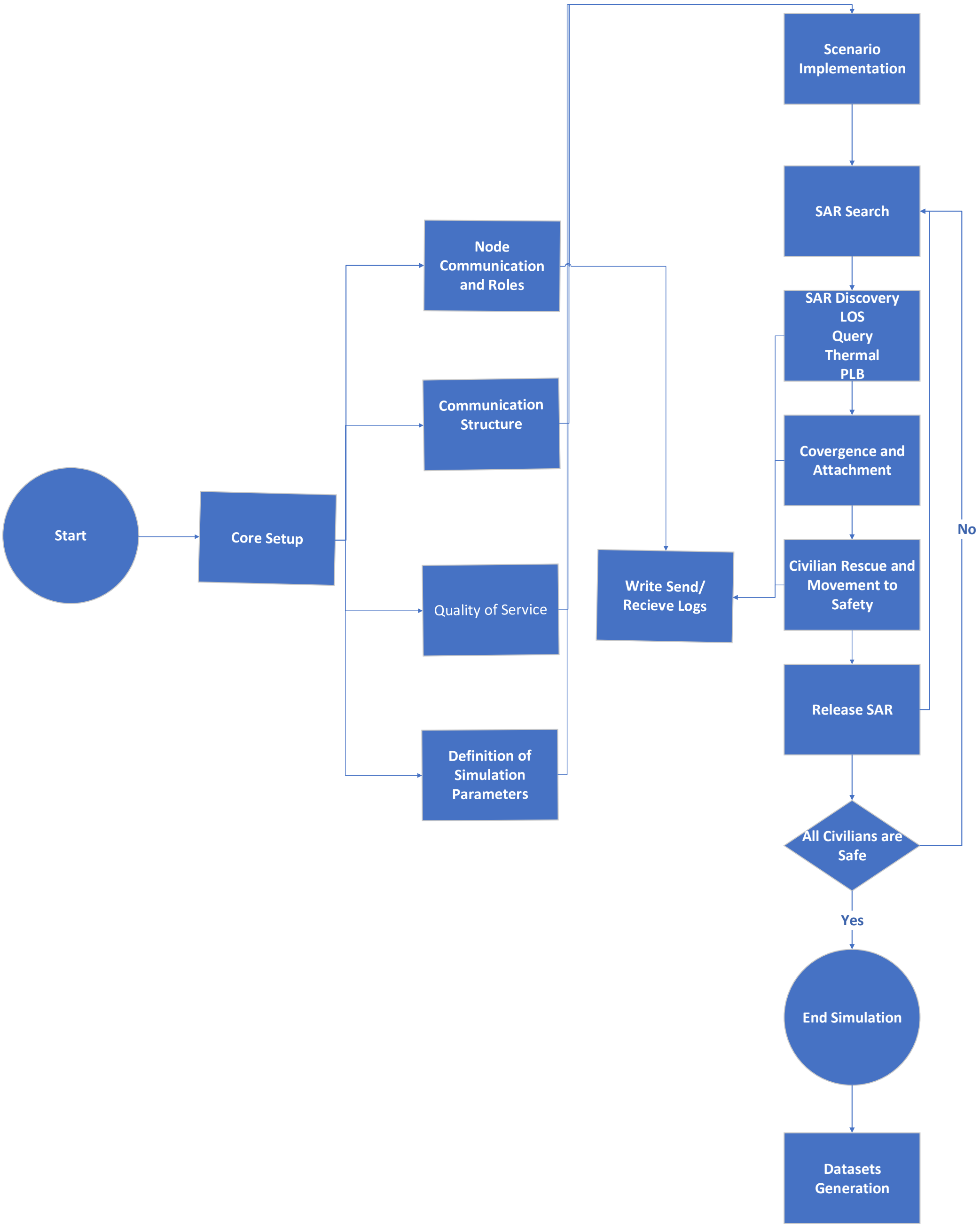

Figure 1: Framework Structure

2.1. Framework: Core Setup

The core framework setup constitutes the foundational layer of our simulation environment, independent of any specific mission. It consists of the configuration of node roles, communication modalities, mobility models, energy profiles, and quality of service mechanisms. This abstraction is designed to be modular and adaptable. The subsections below present each of these components in detail.

2.1.1. Node Communication and Roles

In the proposed framework, nodes are classified by operational role, enabling modular, scalable deployment of SAR scenarios. This role-based structure allows for dynamic adjustment of node counts without altering the core simulation logic, aligning with established SAR practices that emphasise functional task division and differentiated communication [18, 19].

SAR operations, in the literature, are typically organised by node type such as aerial or ground units [19, 20, 21] or by tactical zones with designated tasks and mobility patterns [18]. Our framework configures each node type with specific mobility models, communication technologies, and energy constraints to ensure realistic behaviour. The roles are summarised below:

- **Base Station**: A central coordination hub for the SAR mission. It manages task assignments, logs discovery events, and centralises all communications from SAR teams, drones, and vehicles. It operates without energy constraints.

- **Drones**: Low-altitude aerial units responsible for real-time video and environmental monitoring. Their primary role is civilian discovery.

- **Helicopters**: High-altitude units providing broad-area reconnaissance, long-range communication support, and weather condition monitoring.

- **SAR Vehicles**: Ground-based, off-road mobile units involved in search and rescue. They transmit GPS updates, voice, and video data to the base station to support coordination.

- **Foot Teams**: Mobile ground personnel engaging directly with civilians and other SAR units. Crucial for on-the-ground search, rescue, and evacuation.

- **Civilians**: Represent individuals in need of rescue. They may be static (trapped) or mobile (displaced), and use distress beacons or query-response systems to signal their presence, requiring varied discovery mechanisms.

2.1.2. Communication Structure

The SAR simulation incorporates diverse communication mechanisms that support real-time tracking, coordination, and discovery [22]. These include unicast and broadcast transmissions, each defined by sender, receiver, purpose, and data format. A summary of the communication structure for the whole framework is provided in Appendix A.

GPS Updates: Real-Time Position Tracking. All SAR units periodically transmit GPS packets with their X, Y and Z coordinates. The base station listens on a dedicated port to build a live map of SAR positions. This ensures coordinated movement, reduces redundant searches, and enables mobility analysis. All updates are logged for post-simulation evaluation.

Video Streaming. Drones and vehicles stream video data to the base station, either continuously or at intervals, enhancing situational awareness of terrain, obstacles, and the presence of civilian.

Voice Communication. Simulating radio-like interaction, SAR units exchange voice packets with the base station or other teams. This enables tactical coordination and verbal instructions.

Environmental Data. Drones and helicopters transmit sensor data, such as temperature, humidity, and wind speed to the base station for monitoring weather conditions.

Communication Logging. All transmitted and received packets are logged, capturing key attributes for later analysis.

2.1.3. Quality of Service (QoS)

We implemented QoS in NS-3 using IEEE 802.11e Enhanced Distributed Channel Access (EDCA) for Medium Access Control (MAC) layer prioritisation and Differentiated Services Code Point (DSCP) tagging at the IP layer. Critical SAR traffic such as distress signals, voice communication, and GPS data, was mapped to high-priority queues, while non-urgent data including video streams and environmental logs was assigned lower ones. This ensured prioritised access and reduced delay for mission-critical communication (see Appendix B for class mappings).

2.1.4. Network Simulator Selection and Definition of Simulation Parameters

Choice of NS-3 for Network Simulation. NS-3 was selected due to its open-source nature, modular architecture, and widespread adoption in both academia and industry [23, 24, 25]. It supports a wide range of wireless standards and enables integration of custom models, protocols, and algorithms, making it ideal for simulating complex MANETs scenarios.

Simulation Replicas. To ensure statistical robustness and capture variability in mobility and communication, we conducted ten independent simulation runs using `SeedManager::SetRun(runNumber)`. This approach maintains comparability while introducing controlled randomness. Key metrics, such as completion time, throughput, and signal degradation, were averaged across runs to obtain stable performance indicators [26, 27].

Simulation Parameters. The simulation area covers $1000\,\mathrm{m} \times 1000\,\mathrm{m}$, and represents a mixed urban environment that includes open spaces, buildings, and trees. Communication is established using Wi-Fi (IEEE 802.11n), where each node's transmission power and sensitivity determining effective range. No fixed range is enforced; instead, realistic values and propagation models define link quality.

We implemented two versions of the framework: one in open space, and another with terrain featuring commercial, office, and residential buildings. The *Hybrid Buildings Propagation Loss Model* [28] and *Building Module* [29] were used to model signal attenuation from structures and trees, introducing realistic shadowing and multipath effects.

The simulation is terminating [26]; it ends when all civilians have been successfully rescued. A full list of parameters is summarised in Table 2.

Parameter	**Description**
Simulation Area	1000m × 1000m
Terrain Composition	(1)Includes commercial, office, and residential buildings with varying heights and materials to simulate real-world shadowing. Also includes tree-like obstacles and environmental clutter (2) Free Space
Propagation Loss Models	*Free Space* (V1) and *Hybrid Buildings Propagation Loss Model* (V2) integrated with NS-3's Buildings Module to simulate attenuation, reflection, and multipath interference
Propagation Delay Model	Constant Speed Propagation Delay Model
Mobility Model	Constant Mobility Model and Random Way Mobility Model
Wireless Technology	IEEE 802.11n
Routing Protocols	OLSR, AODV, and DSDV
Communication Range	Dynamically configured based on physical layer parameters, transmission power, receiver sensitivity, and propagation loss model
Simulation Type	Terminating simulation

Table 2: Summary of Simulation Environment and Communication Parameters

Mobility Models and Node Movement. Each node type adopts a mobility model aligned with its operational role. The base station is stationary and serves as the mission control centre. SAR units follow the `Random Waypoint Mobility Model` with predefined pause times and speed ranges. Drones maintain a flight altitude of around 100 m, while helicopters operate at 150 m to provide wider coverage.

Civilians are modelled in two categories: *static*, positioned inside buildings to simulate trapped individuals, or *mobile*, utilising the Random Waypoint simulate to mimic displacement or wandering behaviour.

Battery Configurations. Energy modelling is essential for representing realistic SAR operations. Each node is assigned a power source based on its role and hardware constraints. We adopt the battery implementation from [30], attaching the `WifiRadioEnergyModel` to track energy consumption during transmission, reception, idle, and sleep states. Battery types were selected to resemble real-world devices, as described below. (see Appendix C for a full battery chemistry summary):

- **Base Station:** Assumed to have unlimited power to ensure uninterrupted mission coordination.
- **Helicopters and Vehicles:** Powered by Lead-Acid batteries, reflecting real-world vehicular systems.

- **Drones:** Utilise lightweight Li-ion batteries, selected for their high energy-to-weight ratio.
- **Foot Teams:** Equipped with NiMH batteries [31], commonly used in portable field radios.
- **Civilians with PLBs:** Simulated with NiCd batteries due to NS-3's lack of $LiMnO_2$ support, despite the latter being common in modern PLBs.
- **Civilians with Query Devices:** Assigned Li-ion batteries [32], similar to those in modern mobile devices.

2.2. Framework: Scenario Implementation

This section presents the implementation of SAR operations using our proposed framework. The process begins with the search for and discovery of civilians, followed by the assignment of SAR units to initiate rescue. Once a unit is assigned, it travels towards the civilian and attaches to them, then moves together toward the designated safe zone, in our case, the base station. The following subsections provide a detailed breakdown of each stage in the process.

2.2.1. Search and Discovery

In the context of SAR operations, discovering civilians in need of assistance is critical. This process is designed to be robust, flexible, and adaptive to different conditions, including weather impacts and node capabilities. The framework utilises four distinct discovery mechanisms, categorised as either passive or active. In this context, passive discovery refers to methods in which SAR nodes detect civilians without recieving explicit transmission from them, whereas active discovery involves civilians emitting signals or responding to queries that SAR nodes can detect.

These mechanisms enable SAR nodes to locate civilians through complementary techniques: line-of-sight scanning and thermal imaging for passive discovery, and beacon broadcasts and query-response for active discovery. This integrated approach enhances resilience to terrain obstructions, mobility constraints, and environmental variability. Each method is described in detail below.

Passive Discovery Methods. (1) LOS Discovery: LOS scanning relies on direct visual contact between SAR nodes and civilians. Drones and helicopters, operating at higher altitudes, provide broader LOS coverage compared to foot teams or vehicles, which may be blocked by buildings or terrain. At predetermined intervals, SAR units systematically scan their surroundings. When a civilian is detected within range, a discovery log is generated that records the timestamp, node identification, civilian identification, and distance. This event is then transmitted to the base station to initiate rescue coordination.

(2) Thermal Imaging Discovery: In conditions of limited visibility, thermal imaging enables nodes to detect heat signatures through physical barriers. Thermal scans are conducted periodically and can be configured by radius, providing discovery capabilities that are less affected by obstacles than line-of-sight methods. Upon detection, a log is generated and transmitted to the base station and other SAR units.

Active Discovery Methods. (1) Radio Beacon Broadcasting: Civilians equipped with PLBs periodically broadcast distress signals. SAR nodes monitor these signals and, upon detection, record the event, estimate the distance to the civilian, and alert the base station. PLBs function as reliable, short-range devices that require no civilian interaction beyond initial activation.

(2) Query-Response Discovery: In this mode, SAR nodes periodically broadcast query messages. Civilians respond only upon receiving a query and if they are capable of transmitting. This bidirectional method reduces network congestion and conserves civilian device energy but depends on successful message exchange. Obstructed or inactive devices may delay detection until conditions change.

During all discovery events, SAR nodes maintain detailed logs of operations, including local records of discovery, transmission, and reception activities. These logs enable subsequent performance analysis and troubleshooting.

Once a discovery is processed by the base station, a rescuer is assigned to the civilian, marking the start of the rescue phase.

2.2.2. Rescuer Assignment

Once a civilian is discovered, rescuer assignment follows either a centralised or decentralised approach. In the centralised method, the base station records the discovery and selects a SAR node based on proximity, availability, and role priority. In the decentralised method, if no assignment is received within a configurable timeout period, the node that discovered the civilian assigns the task to itself. This mechanism ensures operational continuity during network disconnections. The assignment logic is extensible and can incorporate constraints, such as restricting assignments to ground units only.

The assignment packet contains the civilian's ID, coordinates, assigned SAR node ID, and a timestamp. This packet is transmitted directly to the selected node and broadcast to all other nodes to enhance situational awareness. A local log is created to record the operation, and the framework is designed to prevent redundant rescue efforts.

2.2.3. Convergence on the Civilian

The designated SAR node proceeds to the convergence phase, navigating toward the civilian's last known location. During this phase, it transmits periodic position updates to the base station, documenting its own location, the civilian's location, the distance between them, and a timestamp. These updates provide real-time information regarding operational progress and any observed delays.

As the SAR unit approaches the target, it continuously monitors the distance to the civilian. Upon reaching a predefined proximity threshold, the system initiates the attachment phase.

2.2.4. Civilian Attachment

Attachment marks the moment the SAR node reaches the civilian and is prepared to initiate transport. The node transmits an attachment packet to the base station, which includes the SAR node ID, civilian ID, and a timestamp. This information is broadcast across the network to prevent duplication, and a local attachment log is generated to document responsibility.

2.2.5. Movement Towards Safety

Once the civilian is attached, the SAR node initiates the return journey. It transmits continuous movement updates to the base station, including node ID, civilian ID, and current coordinates. The data facilitate trajectory logging and arrival time estimation, while local logs are maintained to ensure complete traceability.

2.2.6. Civilian Marked as Safe

Upon arrival at the safety zone, the SAR node transmits a completion packet to the base station to confirm the rescue. The civilian is then marked as safe, removed from the active search list, and the SAR node is released for reassignment. The base station broadcasts this updated status to all nodes to prevent redundant rescue attempts. The event is locally logged, including the civilian ID, SAR node ID, and timestamp.

2.2.7. Data Information Logging

Comprehensive logs are maintained throughout the process to support post-simulation analysis. Each log entry includes the event type, event timestamp, and identifiers for both the SAR node and the civilian. The coordinates of both nodes (X, Y, Z) are recorded at each stage, as well as the distance between them when relevant. The civilian's status, such as discovered, attached, or marked safe, is also documented to ensure traceability and enable precise evaluation of the workflow.

3. Framework Implementation

We implemented two scenarios, referred to as **V1** and **V2**, to evaluate the framework's performance and flexibility. **V1** uses NS-3's *Free Space Propagation Loss Model* [33], which assumes ideal, unobstructed wireless communication. **V2** incorporates the *Hybrid Buildings Propagation Loss Model* [28], simulating signal attenuation due to structural obstructions. Using NS-3's *Building Module* [29], we introduced vertical and horizontal barriers, such as buildings and trees, to influence both line-of-sight and signal strength. This setup shows the framework's ability to model diverse environments without altering core components.

The following subsections outline the selected routing protocols, mobility model, and evaluation metrics used to assess adaptability and performance.

3.1. Routing Protocols

Routing protocols for MANETs are generally classified into three categories: proactive (table-driven), reactive (on-demand), and hybrid [34]. Common protocols include AODV, DSR, DSDV, OLSR, and TORA [35, 36]. Proactive protocols maintain continuous routing tables, while reactive protocols establish routes only when needed [37]. The performance of these protocols varies depending on network size, mobility, and traffic intensity [34].

To evaluate the framework's adaptability, we implemented and tested three widely adopted routing protocols:

- **Destination-Sequenced Distance Vector (DSDV)** [38, 39, 40, 41]: A proactive routing protocol derived from Bellman-Ford, with added sequence numbers to prevent routing loops and ensure freshness. Nodes maintain routing tables and periodically broadcast full or incremental updates. Broken routes are invalidated with a special update using an infinite metric. DSDV offers immediate route availability, minimising discovery delays. However, its continuous updates introduce overhead, especially in high-mobility scenarios; therefore, it is best suited for small to moderately dynamic networks.

- **Optimised Link State Routing (OLSR)** [38, 41]: A proactive link-state protocol optimised for MANETs through multipoint relays (MPRs), which reduce redundant transmissions. Nodes exchange periodic Hello and topology control (TC) messages to maintain up-to-date routing tables and compute shortest paths. OLSR enables low-latency communication and performs well under high traffic. However, it generates continuous control overhead and assumes bidirectional links, performing best in dense topologies.

- **Ad hoc On-Demand Distance Vector (AODV)** [42, 43, 41]: A reactive protocol that initiates route discovery only when needed. It uses broadcasted Route Request (RREQ) messages and replies with Route Reply (RREP) upon discovering a valid path. Sequence numbers ensure loop-free, fresh routes, while Route Error (RERR) messages handle link failures. Although AODV minimises idle-time overhead and scales efficiently, it introduces route acquisition delay during initial transmission. [44].

The routing protocols selected for evaluation represent widely adopted MANETs routing approaches [45] and provide a well-established baseline for comparative analysis. These protocols serve to demonstrate the capabilities of the proposed framework, rather than to provide an exhaustive comparison of all available protocols. Hybrid routing protocols were excluded from this study to maintain a focused and interpretable baseline evaluation; their integration is identified as an area for future research. The modular design of the framework enables researchers to integrate and assess additional routing protocols with ease.

3.2. Mobility Models

The framework utilises the Random Waypoint Model (RWP) for all nodes to maintain simplicity and enable precise control over movement behaviours, particularly during civilian discovery. RWP is classified as an entity mobility model, in which nodes move independently without coordination or interdependence.

Node Type	**Speed Range (m/s)**	**Pause Duration (s)**
base station	Static	Static
Helicopter	5.0 – 20.0	3.0 – 10.0
Drone	5.0 – 20.0	3.0 – 10.0
Vehicles	5.0 – 10.0	1.0 – 8.0
Foot Teams	2.0 – 5.0	1.0 – 5.0
Civilians	2.0 – 5.0	1.0 – 5.0
Civilians (PLB)	Static	Static

Table 3: Random Waypoint Mobility Model Parameters for Each Node Type.

In RWP, each node selects a random destination, moves toward it at a randomly chosen speed, pauses for a defined duration, and repeats this process [46]. Minimum and maximum speeds are configured for each node type at the start of the simulation, as detailed in Table 3. RWP is widely adopted due to its straightforward implementation and suitability for simulating mobile nodes [47, 48]. However, it exhibits speed decay over time; nodes tend to slow down after repeated pauses, which results in biased performance outcomes [16]. To address this issue, a positive minimum speed is enforced for all nodes, ensuring convergence to a stable steady-state mobility behaviour [49]. Despite this adjustment, RWP remains an abstraction and does not represent obstacle-aware or coordinated movement typical of real SAR operations; it is therefore used here as a baseline mobility model.

3.3. Evaluation Metrics

To evaluate network performance and routing protocol efficiency, we use the following key metrics [50, 51]:

- **Packet Delivery Ratio (PDR %)**: The ratio of successfully received packets at the destination to the total sent packets. Higher values indicate more reliable communication.

- **Packet Loss (%)**: The percentage of packets that fail to reach their destination, often due to congestion, weak links, or suboptimal routing.
- **End-to-End Delay (s)**: The average time a packet takes to travel from source to destination. Minimising delay is essential for time-critical SAR operations.
- **Jitter (s)**: The variation in packet delay. High jitter can impair real-time services like voice and video streaming.
- **Throughput (Mbps)**: The average amount of successfully delivered data per second, reflecting the network's data handling capacity.

As discussed in [52, 53, 54, 55], factors such as propagation loss models, mobility patterns, node density, and environmental obstacles significantly influence these metrics. Therefore, these conditions should be carefully considered when interpreting performance results or replicating the framework.

4. Framework Evaluation: Results and Discussion

This section evaluates the performance of the proposed SAR-MANETs framework under varying environmental conditions and network scales. The analysis focuses on routing reliability and scalability by comparing widely used MANETs routing protocols across ideal and obstructed propagation models, as well as increasing node densities.

4.1. Routing and Network Performance

This subsection presents the performance of three widely used MANETs routing protocols, OLSR, DSDV, and AODV, under two distinct propagation models within the proposed framework. Saleh et al. demonstrated that the performance of routing protocols can change significantly when different propagation loss models are applied [52]. The objective is to analyse how each protocol responds to varying environmental conditions, from ideal free-space communication (V1) to complex urban-like environments characterised by structural obstacles (V2).

Experimental Setup

The simulation comprises 24 nodes: one base station, one drone, one helicopter, five vehicles, seven foot teams, and nine civilians. Node mobility, transmission characteristics, and obstacle interactions are consistent across both V1 and V2. The primary distinction lies in the propagation model, as V2 incorporates urban buildings and tree-like obstacles using the NS-3 *Building* class.

OLSR: Under ideal V1 conditions, it achieved a high PDR of 84.39% with minimal average delay (0.030 s) and low jitter (0.0023 s). In contrast, the introduction of obstacles in V2 resulted in a substantial decrease in PDR to 58.43%. Packet loss increased from 15.22% to 40.28%, and both delay and jitter worsened. These findings demonstrate OLSR's sensitivity to environmental obstructions, likely attributable to its proactive routing approach that depends on stable link states.

DSDV: DSDV also experienced a noticeable decline in performance. The PDR decreased from 63.89% in V1 to 40.71% in V2, while packet loss increased sharply to 57.37% in the obstructed environment. Delay increased from 0.038 s to 0.061 s. These results suggest that DSDV struggles to maintain reliable routes in dynamic, obstructed environments.

AODV: AODV demonstrated greater resilience. Interestingly, its PDR slightly improved in V2, increasing from 67.78% to 68.37%, and throughput also increased marginally. Although delay and jitter increased due to longer route discovery times in V2, overall communication reliability remained stable.

Table 4 presents a summarised comparison of the three protocols under both propagation models.

Protocol	**Version**	**PDR (%)**	**Loss (%)**	**Delay (s)**	**Jitter (s)**	**Throughput (Mbps)**
OLSR	V1	84.39	15.22	0.030	0.0023	1.17
OLSR	V2	58.43	40.28	0.056	0.0115	0.69
DSDV	V1	63.89	34.70	0.039	0.0037	0.92
DSDV	V2	40.71	57.37	0.062	0.0098	0.75
AODV	V1	67.78	31.06	0.095	0.0310	0.42
AODV	V2	68.37	30.84	0.111	0.0378	0.44

Table 4: Performance Metrics for Routing Protocols Under Different Propagation Models (V1: Free Space, V2: Buildings).

4.2. Scalability

To evaluate network scalability and assess the impact of node density on performance, we extended the implementation by categorising the network into three sizes: small (39 nodes), medium (63 nodes), and large (101 nodes). This categorisation aligns with the approach used in [53] and allows for a structured analysis of network behaviour as node count increases. Node mobility, transmission characteristics, and interactions with obstacles remained consistent across both V1 and V2 scenarios described previously. Tables 5 and 6 present the corresponding results.

Small Network: In this setting, the performance across all protocols was generally strong in the V1 scenario, as expected under ideal propagation conditions. OLSR achieved the highest PDR at 91.33%, followed by DSDV (77.79%) and AODV (73.12%). In contrast, under V2, OLSR's PDR dropped to 67.94%, a decline of over 23%, while DSDV showed the most dramatic drop to 46.05%, with a corresponding packet loss increase from 21.80% to 53.30%. Interestingly, AODV maintained a relatively stable PDR, even slightly improving to 75.24% in V2, suggesting greater resilience to physical obstructions.

When comparing overall throughput, all protocols experienced reductions in V2, with OLSR dropping from 1.56 Mbps to 1.11 Mbps, and AODV from 0.74 Mbps to 0.62 Mbps. DSDV, despite its steep drop in delivery ratio, retained relatively high throughput in both versions (1.40 Mbps → 1.17 Mbps), likely due to its regular table-driven communication even when packets are lost. Delay and jitter were consistently lowest for OLSR in both settings (0.0175s and 0.0005s in V1), but increased in V2 (0.0426s and 0.0027s), reflecting the cost of frequent route updates and retransmissions in obstructed environments.

Medium Network: In medium-scale simulations, environmental complexity had a more obvious impact. Under V1, OLSR again outperformed others with a PDR of 83.20%, with DSDV at 62.33% and AODV at 53.67%. However, when buildings and obstacles were introduced in V2, OLSR's PDR dropped to 59.56% and DSDV fell to just 37.72%. AODV, in contrast, showed minimal change, maintaining a stable PDR of 53.48% nearly identical to its V1 performance.

The effects of scaling were also reflected in throughput. OLSR dropped from 0.91 Mbps to 0.53 Mbps in V2, and DSDV fell from 0.66 Mbps to 0.50 Mbps. Although AODV's throughput remained lower overall, the relative change was modest (0.22 Mbps to 0.22 Mbps), reinforcing its adaptability. Average delay and jitter increased across the board, with OLSR seeing delay grow from 0.0397s to 0.0681s and jitter from 0.0013s to 0.0048s. AODV showed more controlled increases in delay (0.1092s → 0.0921s) and jitter (0.0397s → 0.0404s), underlining its suitability for reactive environments where congestion and obstructions exist.

Large Network: As the network size scaled to 101 nodes, all routing protocols experienced a significant performance drop, especially under V2. In the V1 scenario, OLSR still performed best with a PDR of 74.99%, while DSDV and AODV lagged at 44.75% and 28.43%, respectively. However, under V2, PDR fell across all protocols. OLSR declined to 48.45%, DSDV to 26.50%, and AODV plummeted to a low of 22.63%, with a packet loss rate exceeding 76%. This steep decline for AODV is likely due to increased route discovery overhead and greater congestion in the network, particularly when obstructions prevent efficient propagation of control packets.

Throughput patterns mirrored this trend. AODV's throughput fell from 0.03 Mbps to 0.02 Mbps; DSDV dropped from 0.16 Mbps to 0.13 Mbps; and OLSR from 0.32 Mbps to 0.09 Mbps, showing that all protocols suffered in maintaining consistent data delivery under high-density and obstructed environments. Delay and jitter values increased across the board. For OLSR, delay increased from 0.0889s (V1) to 0.1009s (V2), while jitter more than tripled (0.0027s to 0.0088s). AODV also saw jitter increase to 0.0460s in V2, the highest among all protocols and network sizes, indicating substantial variability in communication latency.

Table 5: Scalability Results Under Free Space Propagation Model (V1)

Routing	**Nodes**	**Throughput (Mbps)**	**PDR (%)**	**Loss (%)**	**Delay (s)**	**Jitter (s)**
OLSR	39	1.56	91.33	8.55	0.0175	0.0005
AODV	39	0.74	73.12	26.52	0.0675	0.0276
DSDV	39	1.40	77.79	21.80	0.0192	0.0006
OLSR	63	0.91	83.20	16.55	0.0397	0.0013
AODV	63	0.22	53.68	45.85	0.1092	0.0397
DSDV	63	0.66	62.33	36.99	0.0303	0.0012
OLSR	101	0.32	74.99	24.60	0.0889	0.0027
AODV	101	0.03	28.44	70.98	0.0809	0.0385
DSDV	101	0.16	44.75	54.25	0.0525	0.0019

Table 6: Scalability Results Under Buildings Propagation Model (V2)

Routing	**Nodes**	**Throughput (Mbps)**	**PDR (%)**	**Loss (%)**	**Delay (s)**	**Jitter (s)**
OLSR	39	1.11	67.94	31.52	0.0426	0.0027
AODV	39	0.62	75.24	24.37	0.0631	0.0203
DSDV	39	1.17	46.05	53.30	0.0414	0.0027
OLSR	63	0.53	59.56	39.83	0.0681	0.0048
AODV	63	0.22	53.48	45.86	0.0921	0.0404
DSDV	63	0.50	37.72	61.54	0.0613	0.0034
OLSR	101	0.09	48.45	50.70	0.1009	0.0088
AODV	101	0.02	22.63	76.58	0.0778	0.0460
DSDV	101	0.13	26.50	72.34	0.0775	0.0049

4.3. Discussion of the Results

The observed results across routing and scalability tests reinforce established understanding of MANETs routing behaviour under varying conditions. These findings validate the simulation framework and provide empirical support for previous comparative studies.

Performance degradation of OLSR and DSDV under obstructed propagation (V2) is evident in both the 24-node base scenario and scalability tests. This observation is consistent with Maan et al. [53], reported that proactive protocols are sensitive to topology changes and environmental dynamics. OLSR's reliance on MPRs for overhead reduction becomes a disadvantage in complex environments, where link instability undermines routing tables. In our simulations, OLSR's PDR dropped from 91.33% to 67.93% in small networks and from 74.99% to 48.45% in large networks when transitioning from V1 to V2. These results are consistent with Sharma et al. [56] and Alubady et al. [57], findings that proactive protocols perform well in stable environments but are limited by overhead and sensitivity to link-state changes in obstructed or dynamic scenarios.

DSDV, while moderately effective in V1, underperforms in V2 due to its reliance on periodic table updates. In large, obstacle-rich networks, its PDR dropped to 26.50%, with packet loss exceeding 70%. These results confirm DSDV's limited applicability in highly dynamic or large-scale settings and align with Saleh et al. [52], observation that DSDV performance drops sharply under realistic propagation models.

In contrast, AODV demonstrated strong resilience across both scenarios and network scales. In the base scenario, it was the only protocol whose PDR improved in V2, increasing from 67.78% to 68.37%. In the small network, AODV maintained a stable PDR, ranging from 73.12% to 75.24%.

Even in large, obstructed environments, AODV's on-demand design enabled dynamic route establishment in response to topology changes. Although its PDR dropped to 22.63%, it remained more stable and less affected by control overhead than proactive protocols. This can be attributed to frequent route breakages caused by mobility and obstructions. As a reactive protocol, AODV addresses these disruptions by initiating repeated route discovery and repair processes, which increase control traffic and network congestion, ultimately degrading data delivery performance. These observations confirm findings by Gupta et al. [54], Jha et al. [58], and Mai et al. [55], highlighting AODV's adaptability in highly mobile environments.

However, trade-offs exist. AODV incurred higher delay and jitter, especially during initial route discovery. In both base and scalable setups, its average delay exceeded that of OLSR. This suggests that, although AODV adapts well to network changes, it may not be suitable for latency-sensitive applications without further optimisation.

Interestingly, OLSR remains the best performer under ideal conditions. Kurniawan et al. [59] demonstrated that OLSR outperforms other protocols under the Friis model due to efficient flooding and precomputed routes. The V1 results corroborate this, as OLSR achieved the highest throughput and lowest delay in most V1 cases, including a large network setup where it maintained a 74.99% PDR. MPRs reduce control overhead and enable rapid forwarding, particularly in moderately dense networks.

Mukherjee and Mohapatra [60] further support OLSR's performance in structured mobility settings, noting that it achieves balanced QoS when combined with RandomWaypoint mobility, as in our study. This explains OLSR's performance in V1, where it benefits from stable links and predictable mobility.

Overall, OLSR is optimal for moderate-to-large, semi-dynamic networks with clear line-of-sight but performs poorly under obstructed conditions. DSDV is suitable for small-scale or low-mobility settings but incurs high overhead in large or obstructed networks. AODV is the most resilient and scalable protocol for dynamic, obstructed MANETs, making it well-suited to SAR deployments where adaptability and availability are critical.

What sets our work apart is not merely the replication of known results, but the development of a modular, extensible simulation framework tailored to realistic SAR scenarios. The framework integrates variable propagation models, heterogeneous node types, and mobility-aware role configurations, enabling experimentation across diverse conditions without redesigning simulation components. Its flexibility supports systematic testing under both ideal and obstructed conditions (V1 versus V2) and controlled scalability assessments. By unifying environment modelling, node behaviour, and performance evaluation within a single structure, the framework ensures reproducibility and enables researchers to explore complex trade-offs in MANET routing without compromising scenario fidelity. This level of configurability is essential for advancing SAR-specific MANET research and highlighting the framework's value as both a validation tool and a foundation for future experimentation.

5. Dataset Generation

Our framework generates several structured datasets that capture critical aspects of MANET behaviour in SAR scenarios. The dataset pipeline is modular and organised according to node roles, mobility patterns, discovery processes, and communication events. Detailed graphs for each dataset generation are provided in Appendix D.

Each node is initialised with a specific role, such as drone, helicopter, vehicle, foot team, base station, or civilian. This role determines its mobility model, behaviour type (e.g., discoverer or rescuer), communication parameters (e.g., transmit power and receiver sensitivity), and energy profile. Buildings and trees are incorporated into the simulation environment to model realistic signal attenuation and obstructed line-of-sight conditions.

All subsystems log key events using event-driven callbacks or periodic sampling. At the end of each simulation run, logs are exported as timestamped CSV files with headers, enabling seamless integration into post-processing workflows and supporting reproducible experimentation. The following sections present each dataset, its contents, and potential applications.

Node Information Dataset. This dataset logs the configuration of all nodes, including node ID, type (e.g., drone, vehicle, or civilian), initial and final positions (X, Y, Z), mobility model, speed, communication parameters (transmit power, antenna gain, sensitivity), and energy profile. It is useful for analysing node deployment, coverage, and energy trends by role and mobility.

Mobility Dataset. This dataset tracks all node-level position changes using callbacks. It logs the timestamp, node ID, old/new coordinates, and speed. The data enables analysis of mobility patterns, routing changes, and SAR node behaviour during discovery and rescue operations.

Communication Dataset. This dataset logs every communication session, defined by source and destination nodes, data type (such as GPS, video, or voice), and transport protocol (UDP or TCP). It records delay, bytes transferred, and timestamps for each packet. The dataset outputs session-level metrics including average delay, duration, throughput, and packet loss, supporting QoS evaluation under different traffic loads and protocols.

Discovery and Rescue Dataset. This dataset captures timestamps and IDs of discovering nodes and civilians, discovery method (such as line-of-sight, personal locator beacon, or WiFi), number of SAR nodes involved, assigned rescuers, time from discovery to rescue, and distance travelled. It enables evaluation of discovery efficiency, signal loss impacts, and the effects of terrain and mobility on convergence.

Network Performance Dataset. This dataset is generated using FlowMonitor and includes: flow ID, source and destination node IDs , IP addresses, ports, PDR, throughput, delay, jitter, packet loss, and hop count. It supports benchmarking of routing protocols across various mobility and network conditions.

Energy Depletion Dataset. This dataset tracks node-level energy consumption by timestamp, node ID, energy before and after each transmission or reception, and total energy used. It currently models communication energy only, but it is designed to be extensible. The dataset enables analysis of battery drain across different roles and behaviours.

6. Limitations and Future Work

While the framework provides a robust foundation for SAR-specific MANETs simulations, three key areas require further development.

First, the current use of NS-3's default mobility models does not support obstacle avoidance, allowing ground nodes to move unrealistically through buildings or terrain. In real SAR operations, mobility is constrained by physical obstructions. Integrating obstacle-aware pathfinding and collision avoidance mechanisms would facilitate more realistic movement, especially in urban and forested environments.

Second, the framework does not yet model dynamic weather conditions such as rain, fog, or wind, which can significantly influence signal propagation and mobility. Integrating a weather module would enable simulation of environmental effects on both communication and node behaviour.

Finally, future extensions could include a simplified civilian health or triage metric to represent injury severity and time-critical deterioration. In real-world SAR operations, rescuers often encounter multiple civilians and must prioritise rescue actions under resource constraints.

Although medical decision-making is abstracted in the current framework, the modular design supports such extensions. The convergence phase concludes at rescuer-civilian attachment, offering a defined intervention point where triage logic could be implemented to prioritise civilians based on urgency or survival probability.

This enhancement would facilitate evaluation not only of discovery and attachment success, but also of rescue timeliness and outcome quality, including scenarios in which delayed rescue results in failure despite sustained network connectivity.

7. Conclusion

Our work presents a dynamic simulation framework for Mobile Ad Hoc Networks (MANETs), tailored to Search and Rescue (SAR) scenarios. The framework integrates communication modelling, mobility control, QoS mechanisms, and energy tracking within a modular NS-3 environment, enabling the simulation of diverse and realistic scenarios. It supports heterogeneous node roles and discovery mechanisms, and automatically generates detailed datasets to streamline experimentation and enhance reproducibility.

Our validation experiments confirm the framework's reliability by aligning with established results. Its extensibility enables users to incorporate new routing protocols, environmental factors, and behavioural dynamics. To the best of our knowledge, no prior work offers a unified and reusable simulation environment that simultaneously addresses communication, mobility, energy, and QoS within emergency response contexts.

By addressing this gap, our framework offers a comprehensive foundation for evaluating MANET protocols under complex, mission-critical conditions. It serves as a valuable tool for researchers and practitioners in Search and Rescue, disaster relief, and tactical operations.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to polish the language and improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Appendix A. Framework Communication

Communication	**Purpose**	**Sender**	**Receiver**
GPS Update	Share node's position with base station	All SAR Nodes	base station
Video Feed	Stream camera feed to base station	Drones, Vehicles	base station
Voice Data	Real-time voice messages	Ground Nodes, base station	Other ground nodes / base station
Environmental Data	Weather conditions sent to base station	Drone, Helicopter	base station
PLB Signals	Distress broadcast from civilians	Civilians (PLB)	SAR Nodes listening
Query Broadcast	SAR node pings for Civilians	SAR Node	Civilians
Query Response	Civilians respond to SAR queries	Civilians	Requesting SAR node
Discovery Broadcast	SAR node announces discovered civilian to other SAR	Discovering SAR node	All SAR nodes
SAR → Base "Discovery Log"	Notify Base of discovered civilian	SAR Node	base station
Rescue Assignment	base station picks who will rescue & announces	base station	All SAR nodes
Attachment Broadcast	SAR announces attachment to civilian	Assigned SAR node	Other SAR nodes
Movement Update	Assigned SAR node's step-by-step path to base	Assigned SAR node	base station
Civilian Safety	base station signals "Civilian is now safe"	base station	All SAR nodes
Base → Drone Control	Send navigation & control instructions	base station	Drone

Table A.1: Summary of SAR Network Communication

Appendix B. QoS Prioritisation Using DSCP and EDCA

Communication	**Purpose**	**Sender**	**Receiver**	**Priority Level**	**Access Category (AC)**	**DSCP Value (Hex)**	**Expected Latency**
PLB Signals	Civilians sending distress signals	Civilians	SAR Nodes	Highest	AC_VO (Critical)	0xE0 (CS7)	Lowest
Query Broadcast	SAR searching for civilians based on query response	SAR Node	Civilians	Highest	AC_VO (Critical)	0xE0 (CS7)	Lowest
Query Response	Civilians replying to SAR queries	Civilians	Requesting SAR Node	Highest	AC_VO (Critical)	0xE0 (CS7)	Lowest
Rescue Assignment	Base assigns SAR to rescue	base station	All SAR Nodes	Highest	AC_VO (Command)	0xE0 (CS7)	Lowest
Voice Data	Real-time voice communication	Ground Nodes/Base	Other Ground/Base	High	AC_VI (Streaming)	0xA0 (CS5)	Low
GPS Update	Position updates	All SAR Nodes	base station	High	AC_VI (Telemetry)	0xA0 (CS5)	Low
SAR → Base Discovery Log	Report discovered civilians to Base	SAR Node	base station	Highest	AC_VO (Critical)	0xE0 (CS7)	Lowest
Discovery Broadcast	SAR announces discovered civilians	SAR Node	All SAR Nodes	Medium	AC_BE (Updates)	0x60 (CS3)	Moderate
Attachment Broadcast	SAR confirms civilian attachment	SAR Node	Other SAR Nodes	Medium	AC_BE (Updates)	0x60 (CS3)	Moderate
Movement Update	Assigned SAR reports movement	Assigned SAR Node	base station	Medium	AC_BE (Tracking)	0x60 (CS3)	Moderate
Civilian Safety	Base signals that the civilian is safe	base station	All SAR Nodes	Medium	AC_BE (Safety)	0x60 (CS3)	Moderate
Base → Drone Control	Navigation/control instructions	base station	Drone	Medium	AC_BE (Control)	0x60 (CS3)	Moderate
Video Feed	Live drone/vehicle footage	Drones/Vehicles	base station	Lowest	AC_BK (Background)	0x20 (CS1)	High
Environmental Data	Weather/condition updates	Drone/Helicopter	base station	Lowest	AC_BK (Non-Essential)	0x20 (CS1)	High

Table B.2: QoS Prioritisation in SAR Communications using DSCP and EDCA

Appendix C. Battery Chemistry Summary

Device Type	**Battery Chemistry**
Base Station	BasicEnergySource (1e9 J)
Helicopter Communication System	Lead-Acid (CSB GP1272)
Vehicle Communication System	Lead-Acid (CSB GP1272)
Drone	Li-ion (CGR18650DA)
Handheld Radio	NiMH (HHR650D)
PLB	NiCd (N700AAC)
Mobile Phones	Li-ion (CGR18650DA)

Table C.3: Battery Configurations for Different SAR Node Types

Appendix D. Datasets Generation Guide

Appendix D.1. Node Information Dataset

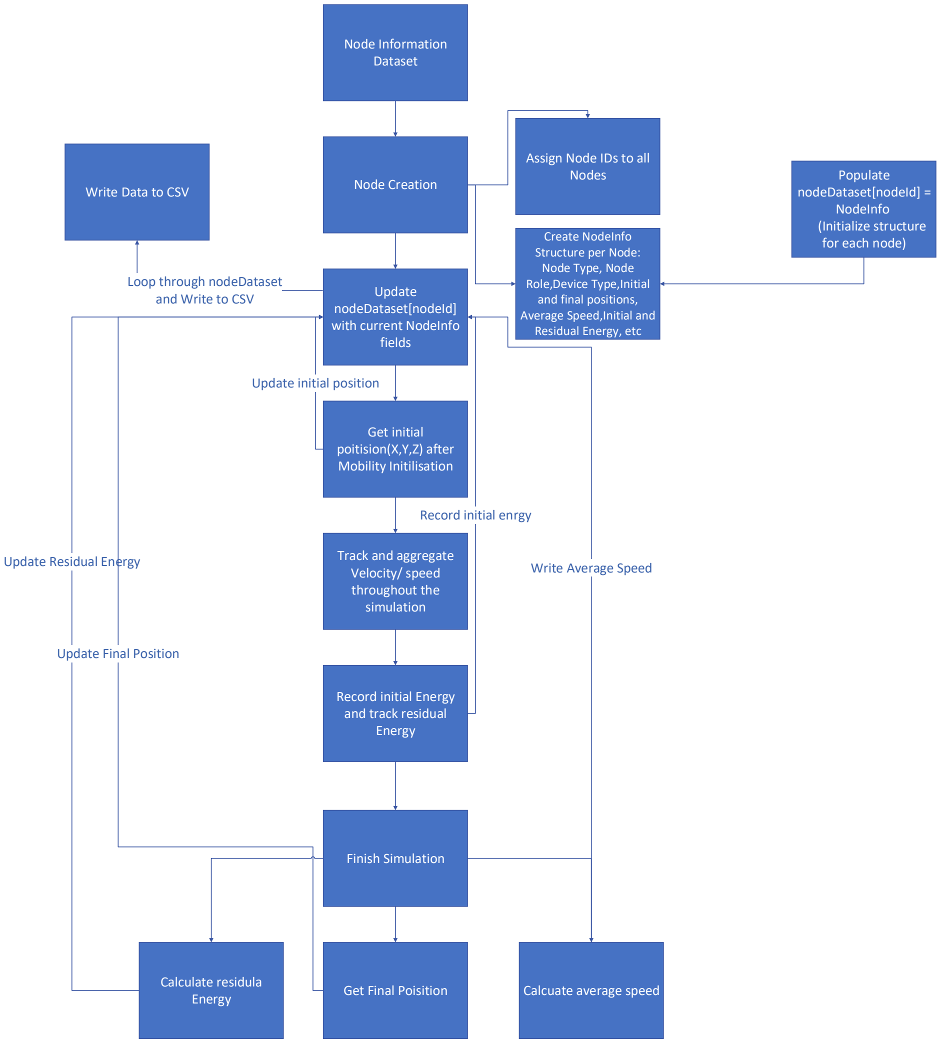

Figure D.1: Node Information Dataset

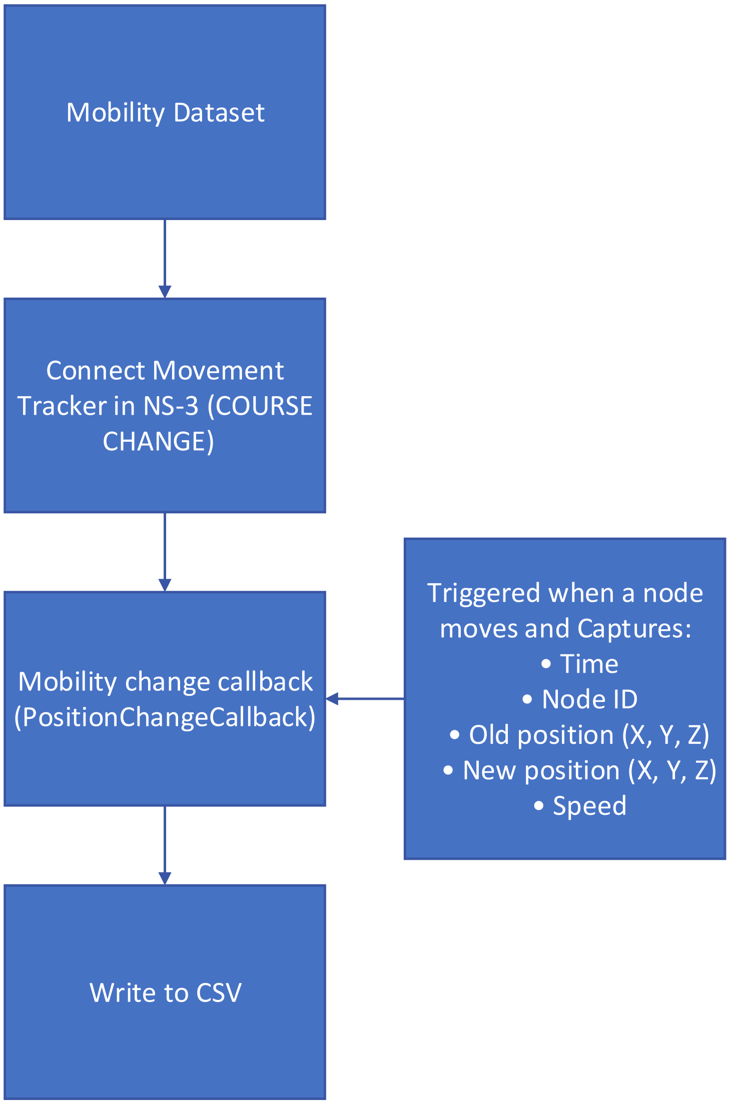

Figure D.2: Mobility Information Dataset

Appendix D.3. Network Performance Dataset

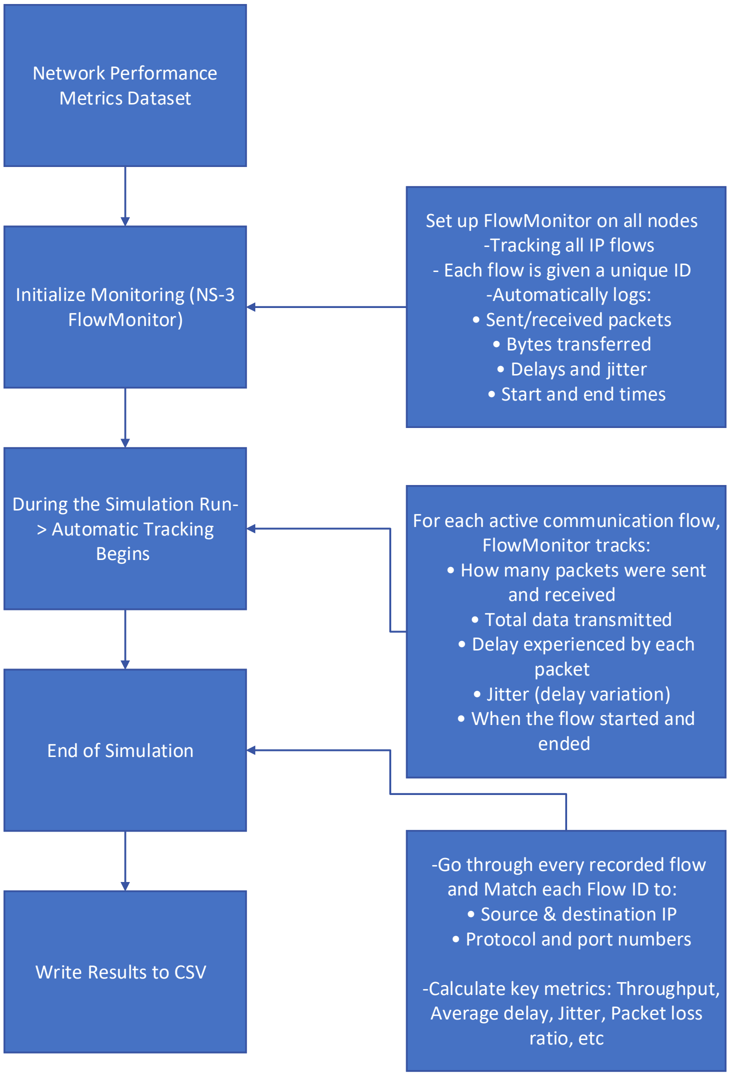

Figure D.3: Network Performance Dataset

Appendix D.4. Energy Dataset

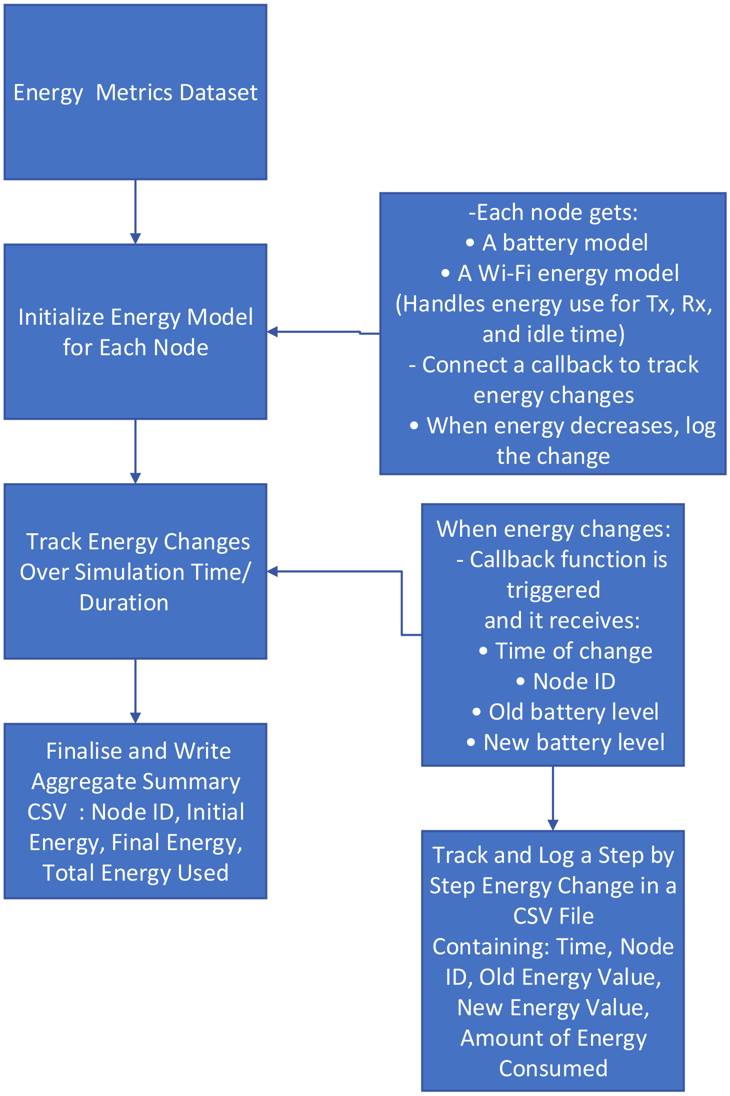

Figure D.4: Energy Metrics Dataset

Appendix D.5. Communication Dataset

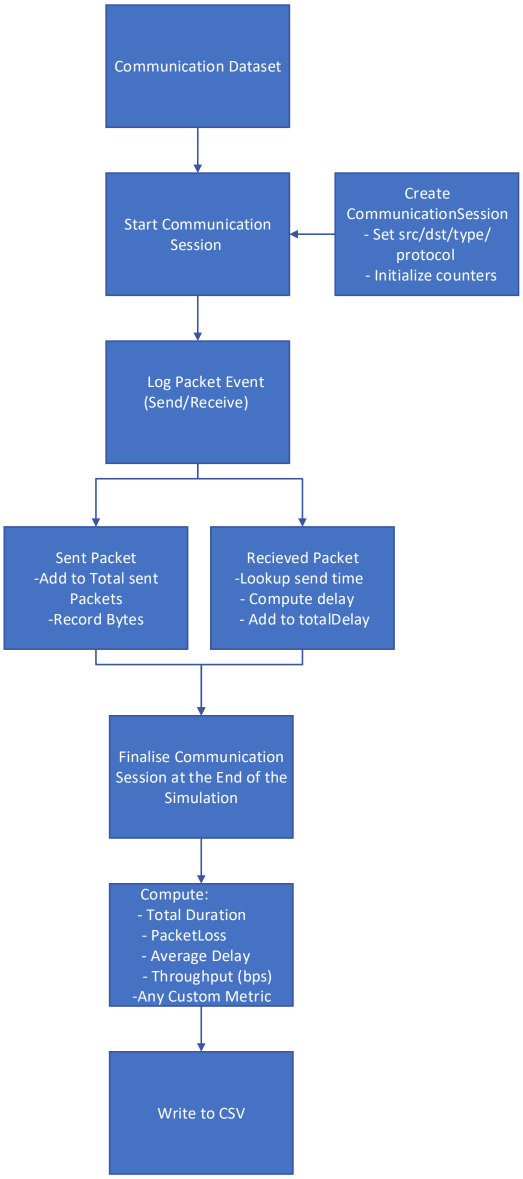

Figure D.5: Communication Dataset

Appendix D.6. Discovery and Rescue Dataset

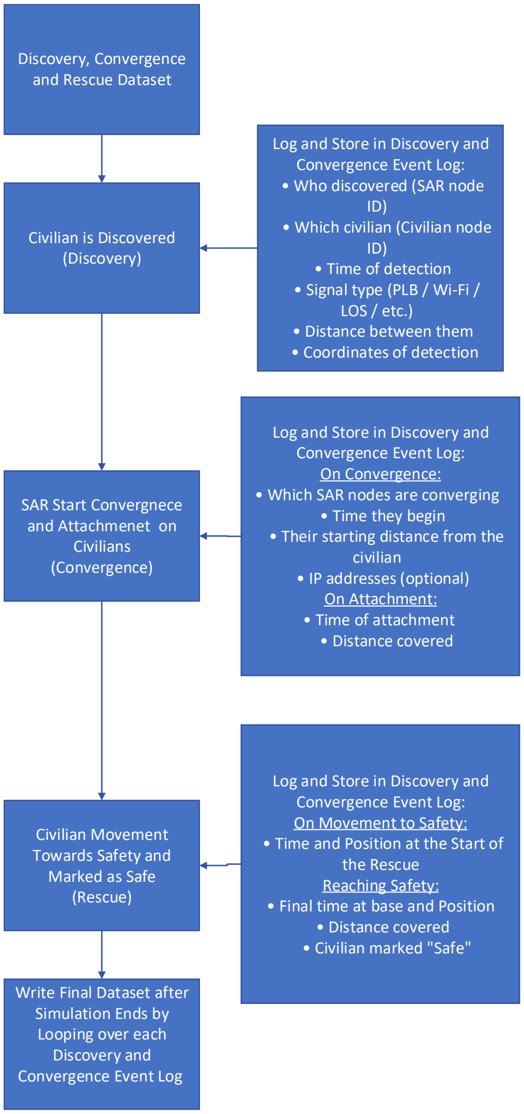

Figure D.6: Discovery and Rescue Dataset