



Performance analysis of cluster-based multi-UAV routing protocol under various mobility models using NS-3

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Article Info

Keywords:

Clustered-based Multi-UAV, Inter-UAV Communication System, NS-3, Routing Protocol, Mobility Model, QoS

Article history:

Received: September 24, 2025

Accepted: February 08, 2026

Published: May 01, 2026

Cite:

H. Darmawan, P. Kristalina, and M. Z. Samsono Hadi, "Performance Analysis of Cluster-based Multi-UAV Routing Protocol under Various Mobility Models using NS-3", *KINETIK*, vol. 11, no. 2, May, 2026. <https://doi.org/10.22219/kinetik.v11i2.2507>

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Abstract

In this paper, the performance of a cluster-based multi-UAV communication system is analyzed as a means to enhance network reliability and coordination in support of Search and Rescue (SAR) operations within disaster-affected areas. The proposed approach addresses the challenges of maintaining connectivity, ensuring efficient data transmission, and facilitating effective collaboration among UAVs in critical environments. The system is designed with a four-layer architecture: Base Station (BS), Cluster Head (CH), Clustered Drone (CD), and User Equipment (UE). These layers are modeled and evaluated using Network Simulator 3 (NS-3). Three routing protocols, namely OLSR, AODV, and DSDV are evaluated under three types of UAV mobility models: Gauss-Markov, Random Waypoint (RWP), and Reference Point Group Mobility (RPGM). Quality of Service (QoS) parameters for wireless networks, such as throughput, packet delivery ratio (PDR), delay, and packet loss, are analyzed under several cluster-based UAV scenarios. The simulation results show that the cluster-based multi-UAV model using OLSR routing protocol achieves the best performance under the RPGM mobility model, with an average throughput of 67.57 kbps, 87.47% PDR, 86 ms delay, and 12.53% packet loss, outperforming the other routing protocols. The OLSR routing protocol demonstrates the highest consistency, with higher throughput and PDR values, as well as lower delay and packet loss compared to AODV and DSDV, particularly in small- to medium-scale node densities. This research contributes to the development of UAV-based cluster communication systems, particularly in terms of efficiency, stability, and adaptability to dynamic disaster environments.

1. Introduction

Unmanned Aerial Vehicles (UAVs) have increased significantly in recent years and have been applied in environmental conservation, disaster surveillance, and search-and-rescue (SAR) missions [1]. Initially developed for military purposes, UAV technology now plays an important role in civil applications, emergency response, and creative industries [2] [3]. The primary advantages of UAVs include high mobility, compact size, and the ability to perform surveillance and communication support in areas lacking network infrastructure, making them an effective solution for disaster-affected regions [4], [5].

In natural disaster cases such as floods, earthquakes, or storms, UAVs are capable of providing situational awareness to assist rescue teams in identifying affected areas and locating victims [6]. However, a single UAV is often insufficient in large-scale disasters. Therefore, multi-UAV systems are required to extend coverage and enable more reliable inter-UAV communication [7].

Despite the advantages of multi-UAV systems, maintaining reliable communication performance remains a major challenge. The primary issue lies in ensuring Quality of Service (QoS) for inter-UAV communication as well as communication between UAVs and ground user devices [8]. Previous studies suggest that existing approaches may still be suboptimal in maintaining inter-UAV connectivity, tracking user devices, and delivering data efficiently to a base station, particularly in dynamic and large-scale deployment scenarios [9]. Moreover, many studies evaluate routing protocols or mobility models independently, without sufficiently considering their combined impact on clustered multi-UAV communication systems operating in disaster environments. Consequently, identifying an effective combination of mobility models and routing protocols to maintain stable QoS in cluster-based multi-UAV networks remains an open research problem. To improve multi-UAV communication performance, selecting appropriate mobility models and routing protocols is critically important [10].

In real-world conditions, UAV mobility is subject to environmental disturbances such as wind, which can alter flight trajectories and disrupt inter-UAV link stability. Furthermore, communication quality among UAVs is strongly influenced by the choice of routing protocol, which determines how data packets are forwarded across the network.

Both of these challenges are addressed in this study through the proposed network simulation framework. In network simulations, mobility models represent UAV movement dynamics that significantly influence topology changes and communication performance. Commonly used models include Random Waypoint (RWP), which represents stochastic movement; Gauss–Markov, which generates smoother and more realistic mobility patterns; and Reference Point Group Mobility (RPGM), which simulates coordinated group movement guided by a Cluster Head (CH) [11]. Routing protocols also play a vital role in maintaining communication quality. Proactive protocols such as Optimized Link State Routing (OLSR) periodically update routing tables to ensure route availability [12] [13], while Destination-Sequenced Distance Vector (DSDV) employs sequence numbers to maintain routing consistency [14]. In contrast, reactive protocols such as Ad hoc On-Demand Distance Vector (AODV) establish routes only when required, reducing overhead at the cost of initial route discovery delay [15]. Therefore, integrating suitable mobility models and routing protocols is fundamental to ensuring reliable and efficient multi-UAV communication.

Based on these foundations, this study aims to identify the most effective mobility model and routing protocol for cluster-based UAV communication in disaster SAR environments. To achieve this, the proposed network simulation framework provides an integrated evaluation across multiple configurations. Specifically, this work (i) jointly analyzes the impact of different UAV mobility models within a hierarchical clustered topology, (ii) systematically compares proactive and reactive routing protocols under identical network conditions, and (iii) derives QoS-driven insights to identify the most stable mobility–routing combination for small- to medium-scale multi-UAV deployments in disaster environments [16].

2. Research Method

The research methodology implemented in this study is divided into two primary stages, namely the design stage and the evaluation stage. In the design stage, the system architecture, mobility models, and routing protocols are defined and configured to align with the objectives of the study, whereas in the evaluation stage, simulations are conducted to assess the performance of the proposed cluster-based multi-UAV communication system, focusing on the impact of different mobility models and routing protocols on the Quality of Service (QoS) metrics.

2.1 Design Stage

The proposed system topology is designed with four hierarchical layers: the Base Station (BS) layer, the Cluster Head (CH) layer, the Clustered Node layer, and the User Equipment (UE) layer. At the Base Station layer, the base station serves as the central controller for UAV operations and as the primary storage unit for data collected from disaster-affected areas. It records and stores all incoming information, manages UAV deployment by issuing operational instructions, and coordinates the dissemination of processed data to relevant emergency response agencies [17], [18]. At the Cluster Head layer, a Cluster Head (CH) is selected from the clustered nodes to act as a bridge between the clustered drone and base station [19]. One cluster head is selected from a group of drones based on the energy consumption of each drone [20]. Under conditions where network infrastructure is unavailable, this layer serves as a communication bridge between the base station and the cluster layer. By leveraging LTE/5G networks at this level, the system gains greater flexibility and improved resilience, thereby ensuring reliable operation in disaster-affected environments where conventional infrastructure is disrupted [21][22].

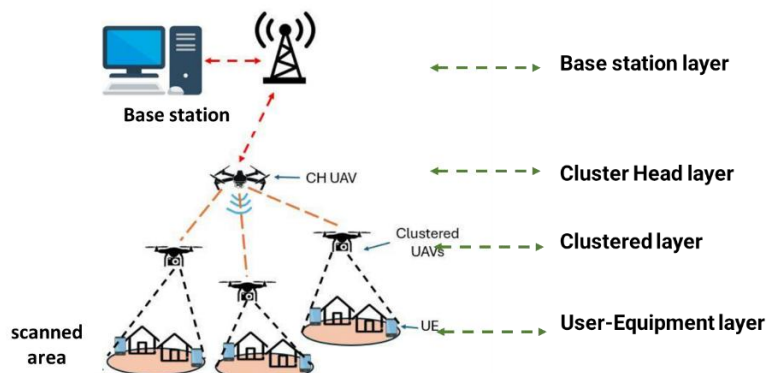


Figure 1. Four Layers Topology for Multi-UAV Clustered-based System

At the clustered layer, UAVs are equipped with onboard camera sensors to scan the target areas and transmit the recorded data to the base station via the CH in real time. A group of UAVs is led by a CH. UAV identity, energy capacity of each UAV, geographic position (the location of each UE device), the number of UE devices in the area, and sensor data collected from each UAV are sent to the CH to be forwarded to the base station [23]. At this layer,

communication technologies are implemented using radio or wireless networks designed to be energy-efficient while maintaining robustness against signal interference [24]. Finally, at the User Equipment (UE) layer, User Equipment represents the communication devices utilized by victims and Search and Rescue (SAR) teams in disaster-affected areas, including mobile phones and other portable communication devices. These devices receive the scanned information from UAVs operating in the field, thereby enabling end users to access situational data for decision-making and response coordination. The overall system design is illustrated in Figure 1.

2.2 Evaluation Stage

The evaluation stage was conducted using network simulations in NS-3 version 3.36.1, with the objective of assessing the performance of the cluster-based multi-UAV communication system under different mobility models and routing protocols. The evaluation process was structured into three parts: simulation parameters, configuration procedures, and simulation configuration and reproducibility.

2.2.1 Simulation Parameters

The key simulation parameters, including simulation time, number of nodes, node velocity, simulation area, mobility models, and routing protocols, communication models, and performance metrics, are presented in Table 1.

Table 1. Simulation Parameter

Parameter	Value
Simulator	NS-3 v3.36.1
Simulation time	600 seconds
Simulation Area	800 m x 800 m x 50 m (3D)
Number of nodes	50,100,150 nodes (BS, Relay Drone, CH, and CD)
Node velocity	CH: 1-4 m/s, CD: 2-6 m/s
Mobility models	BS & Relay: Static, CH & CD: Gauss-Markov, Random Waypoint, RPGM
Routing protocols	OLSR, AODV, DSDV
Communication model	Cellular, Wifi 802.11b
Tx power	16 dBm
Propagation loss model	Friis (LOS)
Traffic type	CBR/UDP, 512 bytes/pkt, 64 kbps
Performance metrics	Throughput, Delay, Packet Delivery Ratio (PDR), Packet Loss

Three simulation schemes were conducted within an $800 \times 800 \times 50$ area, involving clustered drone (CD) deployments of 50, 100, and 150 nodes, as shown in Figure 2. Each cluster was assigned a Cluster Head (CH), which connected to a Relay Drone and subsequently to the Base Station. Cellular communication was employed between the Relay Drone and the Base Station, while Wi-Fi 802.11b was used between the Relay Drone and CHs, as well as between CHs and CDs. Each scheme was evaluated under three mobility models—Gauss–Markov, Random Waypoint, and RPGM—using a fixed routing protocol. Performance of each mobility model and routing protocol was measured in terms of throughput, delay, packet delivery ratio (PDR), and packet loss to determine the optimal combination of routing protocols and mobility models in a cluster-based multi-UAV scheme for disaster environments [25].

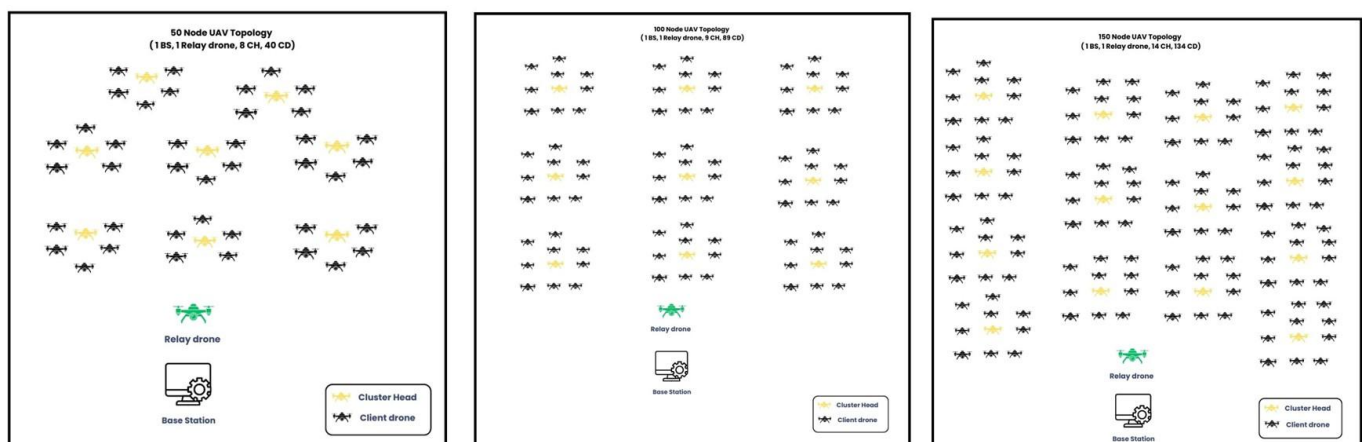


Figure 2. Three Schemes of Node Deployment in Simulation Area

2.2.2 Configuration Procedure

Figure 3 depicts the sequence of steps undertaken in the experimental procedure using the NS-3 simulation tool. The deployment included four node types: Base Station, Relay Drone, Cluster Head (CH), and Clustered Drone (CD). Each node was configured with a NetDevice, MAC protocol, and IP address. Mobility was modeled using Gauss–Markov, Random Waypoint, and Reference Point Group Mobility (RPGM) to evaluate movement effects on communication.

Routing protocols: OLSR, AODV, and DSDV were implemented to manage data transmission from CDs to CHs, relayed through the Relay Drone, and delivered to the Base Station. Performance metrics—throughput, delay, packet delivery ratio (PDR), and packet loss—were collected using FlowMonitor. Each scenario was executed five times, and average results were analyzed to determine the optimal mobility–routing configuration for cluster-based multi-UAV communication in disaster search and rescue operations.

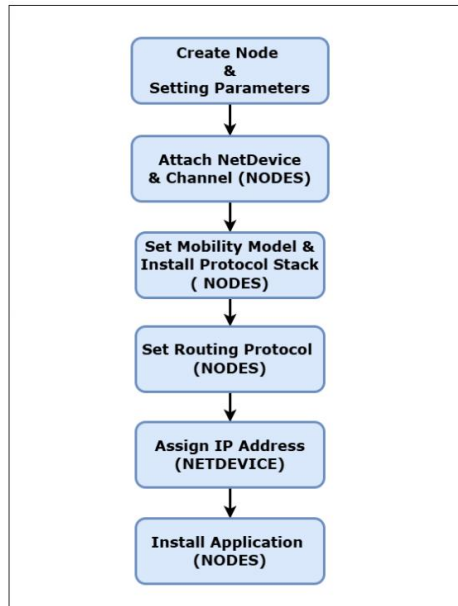


Figure 3. Flowchart of Experimental Procedure using NS-3

2.2.3 Simulation Configuration and Reproducibility

To ensure the reproducibility of the simulation results, this study provides a detailed description of the NS-3 configuration and experimental setup. All simulations were conducted using NS-3 version 3.36.1 in a Linux-based environment. The network stack was configured using IPv4 with standard Internet modules enabled.

Wireless communication between UAV nodes was implemented using IEEE 802.11b, while cellular communication was applied between the Relay Drone and the Base Station. The wireless channel employed a standard propagation loss model with a constant transmission power configuration. Data transmission was generated using UDP traffic, with a fixed packet size and constant packet interval to ensure consistent load across all scenarios. Routing protocols were configured using the default NS-3 helpers, namely OlsrHelper, AodvHelper, and DsdvHelper, and were applied consistently across all mobility models. Mobility behavior was configured as follows: Random Waypoint (RWP) used predefined speed and pause time ranges; Gauss–Markov employed a fixed tuning parameter to control motion smoothness; and Reference Point Group Mobility (RPGM) was implemented with cluster members following a designated reference point representing the Cluster Head.

Each simulation scenario was executed in five independent runs with different random seeds to reduce stochastic bias, and the average values were reported. Network performance metrics, including throughput, packet delivery ratio (PDR), delay, and packet loss, were collected using the FlowMonitor module. This configuration allows other researchers to replicate the simulation scenarios and validate the reported results.

3. Results and Discussion

This section presents the simulation results obtained from nine experimental configurations, each combining one of three mobility models (Gauss–Markov, RWP, RPGM) with one of three routing protocols (OLSR, AODV, DSDV) across three network scales (50, 100, and 150 nodes). The analysis focuses on two key dimensions: the impact of mobility models on QoS, and the comparative effectiveness of routing protocols. All performance data are presented in Figure 4 and Figure 5 to support cross-configuration comparisons.

3.1 Summary of Simulation Result

Table 2 presents the best-performing mobility–routing protocol combination for each node scale. At 50 nodes, RPGM+OLSR achieves the highest PDR (91.6%) and lowest packet loss (8.4%). At 100 nodes, RPGM+AODV delivers the highest throughput (231.89 kbps), while RWP+AODV maintains the highest PDR (88.35%). At 150 nodes, RWP+OLSR achieves the most stable PDR (85.58%) with the lowest delay (11.93 ms). These results confirm that no single combination dominates across all scales, underscoring the importance of scale-aware protocol selection.

Table 2. Simulation Results per Mobility Model, Routing Protocol, and Network Scale

Mobility Model	Routing Protocol	Number of Node	Avg Throughput (kbps)	Avg PDR (%)	Avg Packet Loss (%)	Avg Delay (ms)
Gauss-Markov	OLSR	50	62.7	89.1	10.9	91
Random Waypoint	OLSR	50	58.5	86.9	13.1	97
RPGM	OLSR	50	65.2	91.6	8.4	86
Gauss-Markov	AODV	100	42.39	78.58	4.80	36.20
Random Waypoint	AODV	100	198	88.35	10.97	98.28
RPGM	AODV	100	231.89	67.61	17.42	165.60
Gauss-Markov	OLSR	150	41.30	45	55	126
Random Waypoint	OLSR	150	52.52	85.58	14.42	11.93
RPGM	AODV	150	101.5	82.06	13.73	127.36

3.2 The analysis of the mobility model's impact on clustered node performance

Figure 4 presents the comparative impact of the three mobility models—Gauss–Markov, Random Waypoint (RWP), and Reference Point Group Mobility (RPGM)—on Quality of Service (QoS) performance across different network scales. The results indicate that mobility effectiveness is highly dependent on node density and routing configuration, and no single mobility model consistently dominates across all deployment scenarios.

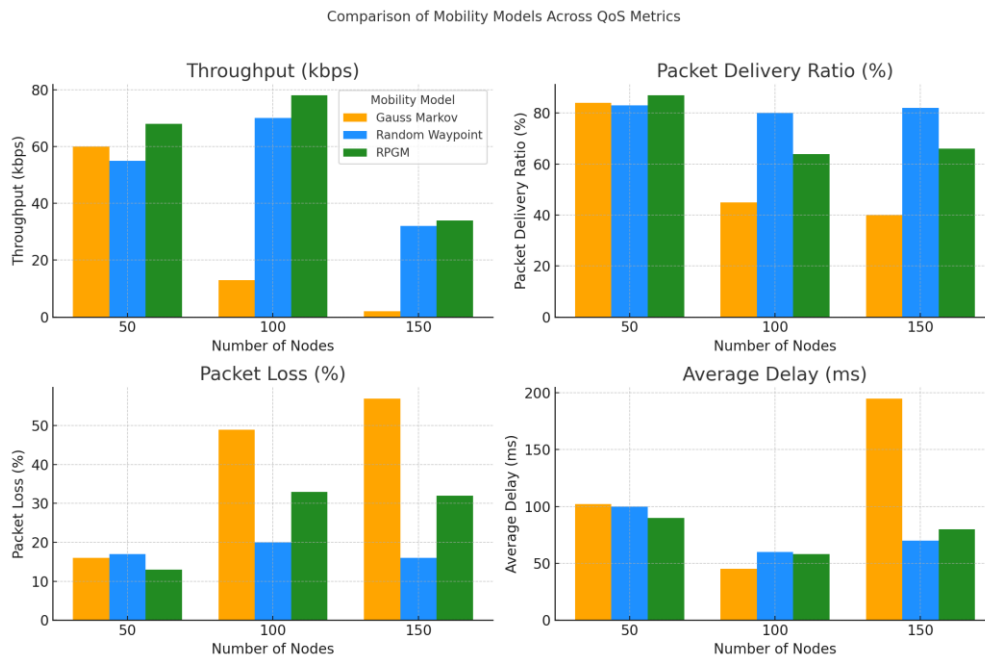


Figure 4. The Comparison of Mobility Model's Impact on Several Performance Metrics

Under the 50-node configuration using OLSR routing, RPGM achieved the best overall performance. As shown in Table 2, RPGM recorded the highest average throughput of 65.2 kbps and a packet delivery ratio (PDR) of 91.6%, while also maintaining the lowest packet loss 8.4% and delay 86 ms. Gauss–Markov followed closely with 62.7 kbps throughput and 89.1% PDR, whereas Random Waypoint yielded slightly lower performance with 58.5 kbps throughput and 86.9% PDR. These results suggest that coordinated group mobility, as implemented in RPGM, enhances intra-cluster link stability in small-scale networks by maintaining consistent relative positioning among clustered nodes.

When the network scale increased to 100 nodes under AODV routing, the performance characteristics changed significantly. RPGM achieved the highest throughput of 231.89 kbps, but this was accompanied by a lower PDR 67.61% and higher delay 165.60 ms. In contrast, Random Waypoint provided a more balanced QoS profile at this scale, delivering 198 kbps throughput and the highest PDR 88.35% with a moderate delay 98.28 ms. Meanwhile, Gauss–Markov experienced substantial throughput degradation, reaching only 2.39 kbps, indicating that individually stochastic mobility may disrupt route stability under medium node density when combined with reactive routing mechanisms.

At 150 nodes, the influence of mobility became more pronounced under higher topology dynamics. Random Waypoint combined with OLSR achieved the highest PDR of 85.58% and the lowest delay of 11.93 ms, although throughput remained relatively low at 2.52 kbps. Conversely, RPGM with AODV produced significantly higher throughput of 101.5 kbps and maintained a competitive PDR of 82.06%, but at the expense of increased delay of 127.36 ms. Gauss–Markov with OLSR demonstrated the weakest performance at this scale, with throughput dropping to 1.30 kbps and PDR decreasing to 45%, indicating reduced suitability for dense clustered deployments.

Overall, the results demonstrate that mobility behavior plays a critical role in maintaining communication stability within clustered UAV networks. RPGM performs optimally in small-scale deployments due to coordinated group movement that preserves cluster cohesion. However, as node density increases, the interaction between mobility patterns and routing strategy becomes increasingly significant. These findings highlight that mobility model selection must be aligned with routing protocol characteristics and deployment scale to ensure stable QoS in disaster-oriented multi-UAV communication systems. Taken together, these findings highlight that mobility-aware cluster design—specifically the alignment between group-based UAV movement and clustered communication architecture—is a decisive factor in achieving reliable QoS for multi-UAV SAR networks [26].

3.3 The analysis of routing protocol’s impact on clustered node performance

Figure 5 presents the comparative routing protocol performance across all mobility models and node scales. The results reveal that protocol choice has a pronounced effect on communication reliability, particularly as network density increases, and that the suitability of each protocol is strongly conditioned by the underlying mobility model.

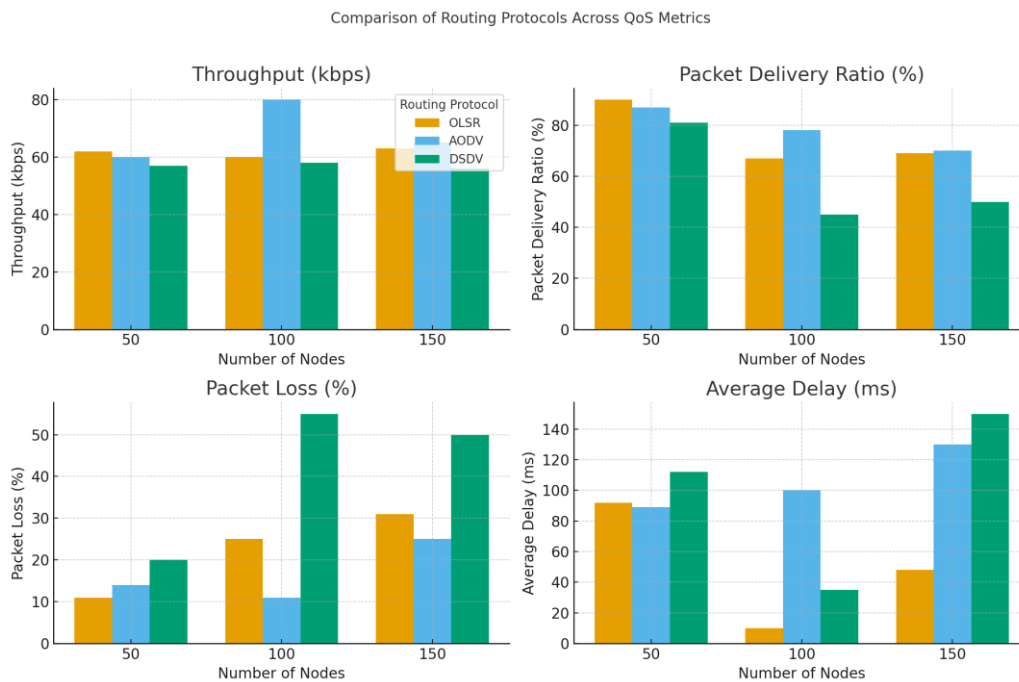


Figure 5. The Comparison of Routing Protocol’s Impact on Several Performance Metrics

At 50 nodes, OLSR demonstrates the best overall balance of QoS performance. It achieves approximately 62 kbps throughput and the highest Packet Delivery Ratio (PDR) of 90%, while maintaining packet loss near 10% and delay around 90 ms. AODV shows a slightly lower PDR of 88% and similar throughput of 60 kbps, with slightly lower delay. DSDV performs the weakest at this scale, with lower throughput around 57 kbps, reduced PDR of 80%, higher packet loss of around 20%, and the highest delay of 110 ms. These results indicate that proactive link-state maintenance in OLSR provides more stable communication in small-scale clustered UAV networks.

When the network increases to 100 nodes, performance divergence becomes more pronounced. AODV achieves the highest throughput of approximately 80 kbps and maintains a relatively high PDR of 78%. OLSR maintains moderate throughput of around 60 kbps with a PDR near 67%. In contrast, DSDV experiences a sharp degradation, with PDR dropping significantly to 45% and packet loss exceeding 50%. Delay for AODV increases to approximately 100 ms, while OLSR shows a notably lower delay of 10 ms. These findings suggest that under medium node density, reactive routing (AODV) can provide higher throughput, while proactive OLSR maintains lower delay.

At 150 nodes, AODV continues to deliver the highest throughput of 70 kbps and maintains a PDR near 70%. OLSR achieves slightly lower throughput of 63 kbps and a PDR near 68%, but with considerably lower delay compared to AODV. DSDV again shows the poorest performance, with a PDR of 50%, packet loss near 50%, and the highest delay of 150 ms. The increasing delay and packet loss under DSDV highlight its scalability limitations in dense and dynamic UAV topologies.

3.4 Comparative Discussion with Related Works

The significance of this study lies in its integrated evaluation methodology, which addresses limitations found in prior research on UAV and FANET communication systems. Most existing studies evaluate either routing protocols under fixed mobility assumptions or mobility models without embedding them in a realistic hierarchical cluster-based UAV architecture. For instance, Kurniawan et al. [12] analyzed OLSR, AODV, and DSDV in a conventional MANET scenario using NS-3. Their results showed that OLSR achieved packet delivery ratios exceeding 97% under low node density conditions. However, their evaluation was conducted without hierarchical clustering and without coordinated group mobility. In contrast, the present study demonstrates that routing performance significantly varies when mobility dynamics and cluster-based topology are jointly considered. Our findings indicate that high PDR values observed in static MANET configurations do not necessarily scale under dynamic multi-UAV SAR deployments. Similarly, Chen et al. [23] provided a comprehensive survey of UAV swarm communication architectures and routing protocols. While their work offers valuable conceptual insights into swarm communication strategies, it does not experimentally quantify how coordinated mobility patterns affect routing scalability and QoS performance across different node densities. The current study extends beyond conceptual review by providing a systematic experimental comparison under controlled simulation conditions.

Compared to mobility-focused research such as A. Joshi et al. [10], which optimized FANET performance using realistic mobility models, and V. Kumar et al. [26], which proposed an improved Gauss–Markov mobility model in 3D FANET environments, this study contributes a broader cross-factor evaluation. While [10] and [26] primarily emphasize mobility realism and trajectory optimization, they do not systematically evaluate the interaction between mobility models and multiple routing protocols within a hierarchical cluster-based UAV structure.

The key contribution of this work lies in the simultaneous evaluation of three mobility models and three routing protocols across multiple network scales within a four-layer clustered UAV architecture. This combinatorial evaluation framework enables the identification of mobility–routing compatibility as the dominant determinant of QoS stability. The results clearly demonstrate that group-coordinated mobility (RPGM) combined with proactive routing (OLSR) yields superior communication reliability in small- to medium-scale disaster SAR scenarios. Such integrated analysis has not been explicitly quantified in prior MANET- or FANET-based studies.

4. Conclusion

This study evaluated the impact of node mobility models and routing protocols on inter-node communication within clustered UAV networks. The simulation results indicate that the Reference Point Group Mobility (RPGM) model delivers superior communication performance compared to the Gauss–Markov and Random Waypoint models, as it maintains more stable movement within cluster structures. In terms of routing protocols, OLSR demonstrates greater consistency, achieving higher throughput and packet delivery ratio (PDR), along with lower delay and packet loss compared to AODV and DSDV. The combination of RPGM and OLSR is therefore identified as the optimal configuration for supporting multi-UAV communication in search and rescue (SAR) operations, particularly in small- to medium-scale networks.

Despite these findings, this study has several limitations. The performance evaluation was conducted solely through simulation using NS-3, which may not fully capture real-world environmental factors such as signal interference, hardware constraints, and unpredictable UAV dynamics. In addition, the network scale and traffic patterns were limited

to predefined scenarios, and energy consumption was not explicitly considered. These factors may influence system performance in practical deployments.

Future work will focus on validating the proposed configuration in real-world UAV communication scenarios. Implementation in disaster monitoring and emergency response environments will enable further evaluation of network stability, detection accuracy, energy efficiency, and reliability under dynamic and unpredictable conditions.

Acknowledgement

The authors would like to express their gratitude to the Directorate of Research and Community Service, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, for the financial support provided for this work. This article is part of a master's thesis research funded under contract number 019/C3/DT.05.00/PL/2025.

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