

Recent Routing Protocols in UAV Networks: Classifications, Challenges, and Future Directions

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Abstract

Routing protocols are really important for unmanned aerial vehicle networks in flying ad hoc networks. These networks are very dynamic. Things change quickly. Unmanned aerial vehicles (UAVs) are always moving. It is hard to keep a stable connection. This is because the connection is often lost and the links break. Also, the UAVs do not have a lot of power, so the routing strategies must be careful with the energy they use. Another thing that is important in flying ad hoc networks is that the number of UAVs in the network can change. The routing protocols must work when there are many UAVs and when there are only a few. They must make sure that the data gets to where it needs to go and that a lot of data can be sent at the same time. This paper looks at the types of routing protocols for unmanned aerial vehicle networks. There are three types: topology-based, position-based, and hierarchical-based approaches. It also looks at ways to improve the network, such as using predictive clustering techniques and energy-aware routing metrics. The study also looks at the problems that unmanned aerial vehicle networks have, like links breaking and the UAVs moving around a lot. It also looks at how to make the network work well when there are UAVs. By comparing the routing protocols using simulations, the study found that the hybrid routing protocols work best. These protocols use a combination of approaches, and they are better at getting packets delivered, sending a lot of data, and keeping the network running smoothly.

Keywords: UAV, Flying Ad Hoc Networks (FANETs), routing protocol, topology-based routing protocols, position-based routing protocols, hierarchy-based routing protocols

INTRODUCTION

Routing protocols are essential for enabling reliable communication in unmanned aerial vehicles (UAVs), particularly in FANETs, where high mobility and dynamic topologies pose unique challenges [1]. These protocols must adapt to rapid changes in node positions, frequent link failures, and energy constraints to ensure efficient data transmission [2]. Routing aims to minimize hops, delay, and energy use while supporting quality of service (QoS) for applications such as surveillance or delivery. Emerging solutions incorporate machine learning or blockchain for trust and recovery from attacks [3]. This study surveys the key classifications, examples, challenges, and performance insights of routing protocols in UAV networks.

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Received Date: March 17, 2026

Accepted Date: April 02, 2026

Published Date: July 20, 2026

Citation: Ali H. Wheeb. Recent Routing Protocols in UAV Networks: Classifications, Challenges, and Future Directions. International Journal of Algorithms Design and Analysis Review. 2026; 4(2): 17–21p.

UAV ROUTING PROTOCOL CLASSIFICATIONS

UAV routing protocols fall into several categories to address FANET characteristics, such as 3D mobility and sparse connectivity. Topology-based routing protocols, the most common, are divided into proactive protocols, such as optimized link state routing (OLSR) and Destination-Sequenced Distance-Vector (DSDV), and reactive protocols, such as Ad hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing

(DSR). Hybrid protocols include Temporally Ordered Routing Algorithm (TORA) and Geographic Routing Protocol (GRP). Proactive protocols maintain constant routing tables but incur high overheads, whereas reactive protocols discover routes on demand for lower initial costs. Hybrid routing protocols in UAV networks combine proactive and reactive strategies to balance the overhead, latency, and adaptability in dynamic FANETs. They proactively maintain partial topology knowledge while discovering routes on demand, making them suitable for high-mobility scenarios such as surveillance or disaster response [4]. Recent topology-based routing protocols for UAV networks include hybrid reactive-proactive schemes enhanced for FANETs' high dynamics, with examples from 2024-2025 demonstrating improved scalability and stability [5]. Table 1 presents recent topology-based routing protocols for FANETs.

Position-based routing protocols use GPS coordinates for greedy forwarding without full topology knowledge, suiting sparse networks by selecting the next hops based on geographic progress toward destinations. Recent position-based routing protocols for UAV networks incorporate hybrid elements and AI for improved link prediction and recovery. Table 2 presents recent position-based routing protocols for FANETs [6].

Hierarchical routing protocols organize UAVs into clusters with leaders, reducing overhead in large swarms through intra- and inter-cluster routing. Recent hierarchical routing protocols for UAV networks have addressed scalability and dynamic topology challenges in large-scale swarms [7]. Hierarchical routing protocols for UAV networks include several specialized designs tailored to FANETs and UAV swarms. Table 3 presents recent hierarchical routing protocols for FANETs and UAV swarms.

Table 1. Recent topology-based routing protocols for FANETs.

Protocol	Year	Main features	Performance evaluation
Inter-Cluster Routing Protocol (ICRP) [5]	2024	Hybrid ant colony algorithm for inter-cluster routing; predictive repair for mobility; pheromone-based path selection	Higher packet delivery ratio (PDR) and lower delay
Machine Learning Routing-FANET (MLR-FANET) [8]	2025	Analyzes topology changes with ML; proactive/reactive hybrid for energy and faults	Better energy efficiency, fault tolerance
Energy/Mobility Optimization (REMO) [9]	2025	Factors residual energy, mobility in cluster routing; reactive discovery	Improved delivery in dynamic clusters

Table 2. Recent position-based routing protocols for FANETs.

Protocol	Year	Main features	Performance evaluation
Position-based hybrid routing protocol (PHRP) [10]	2024	Segment-by-segment greedy forwarding in clustered FANETs; hybrid with topology hints for traffic engineering	Reduces congestion in dense swarms; Scalable multi-path routing
QLR-FANET [11]	2025	Q-learning reinforcement learning (RL) with rate control; location-based next-hop selection adapting bitrate to topology changes	Increase throughput and decrease delay in dynamic environments
Greedy perimeter stateless routing with mobility prediction (GPSR-MP) [12]	2025	GPSR enhanced with predictive positioning and link quality for next-hop relay selection	Higher resilience to high-speed voids; better packet delivery ratio (PDR) in 3D swarms

Table 3. Recent hierarchical-based routing protocols for FANETs.

Protocol	Year	Main features	Performance evaluation
EC-MOPSO [13]	2024	Edge computing-assisted hybrid clustering with Multi-Objective Particle Swarm Optimization for routing in UAV swarms	Better energy efficiency and delay reduction through edge-optimized cluster heads and path selection
CR-UAV (CNRF-based) [1]	2024	Clustering via Central Node Resolution Factor (delay, reliability, energy, mobility prediction); cognitive radio support	Increased throughput, reduced end-to-end delay, better packet delivery ratio (PDR) in high-mobility spectrum-constrained FANETs
DEAR [14]	2025	Joint delay-energy optimization in hierarchical structure; aware of UAV swarm dynamics	Higher throughput, improved normalized routing load over traditional protocols in simulations

Other categories include swarm-based (leveraging bio-inspired behaviors), deterministic (fixed paths), stochastic (probability-driven), and social network-based protocols, each tailored to specific UAV scenarios, such as disaster response or surveillance [15]. The Q-learning-based Stepwise Routing Protocol for Multi-UAV Networks employs reinforcement learning to dynamically select optimal paths by minimizing hops while maximizing link quality. Each UAV acts as an agent, using Q-values updated via rewards from transmission success, delay, and signal strength to learn forwarding policies in real time amid 3D mobility patterns [16].

ROUTING MECHANISMS AND KEY IDEA

AODV, a reactive protocol, broadcasts route request (RREQ) messages and uses route reply (RREP) for on-demand paths, performing well in moderate-mobility UAV setups but struggling with frequent topology shifts [17]. OLSR, which is proactive, optimizes link-state updates via multipoint relays to reduce overhead [18]. Enhanced variants, such as OLSR+GPSR, integrate fuzzy logic for velocity-based adjustments and hybrid greedy perimeter routing [19].

TORA excels in hybrid scenarios with dynamic topology adaptation, outperforming AODV and DSDV in terms of throughput and packet delivery ratio (PDR) under FANET simulations, although it shows a higher end-to-end delay. Advanced protocols, such as the Central Node Resolution Factor (CNRF) scheme in CR-UAV networks, weigh factors such as distance (via RSSI), speed, link delay, reliability, and residual energy to select stable paths and clusters, incorporating predictive mobility to preempt failures [20]. These mechanisms often employ HELLO messages for neighbor discovery, clustering algorithms for scalability, and metrics such as queuing delay or reliability factor for path optimization.

CHALLENGES OF DYNAMIC UAV ENVIRONMENT

High UAV speeds (up to 100 m/s) cause rapid topology changes and link breaks, overwhelming traditional Mobile Ad Hoc Network (MANET)/ Vehicular Ad Hoc Network (VANET) protocols like AODV, which assume lower mobility. Energy limits demand protocols that balance routing overhead with battery life, while 3D space leads to intermittent connectivity and Doppler effects that degrade signals [21]. Security vulnerabilities, such as malicious node detection and scalability in dense swarms, add complexity, and primary user interference in cognitive radio UAVs requires dynamic spectrum access and re-clustering. Simulations reveal that proactive protocols suffer from high control traffic in dynamic FANETs, whereas reactive protocols face discovery latency [22].

CONCLUSION AND FUTURE DIRECTIONS

Routing protocols in UAV networks, including topology-based, position-based, and hierarchical-based routing protocols, address FANET-specific demands through adaptive mechanisms such as multi-metric selection and predictive clustering. Simulations confirm that hybrid and position-enhanced variants excel in throughput, PDR, and delay under high-speed 3D scenarios, outperforming MANET legacies amid link breaks and energy limits.

Open challenges include integrating AI for real-time adaptation and hybrid software-defined networks (SDN) for centralized control in ultra-dynamic swarms. Energy harvesting and quantum-secure routing can extend viability, with simulations urging protocol hybrids for diverse UAV missions. Ongoing research emphasizes QoS guarantees in such environments.

Acknowledgments

The acknowledgments statement gives credit to those who contributed to the manuscript but did not meet the criteria for authorship. Personal communications should include a letter of permission and may be acknowledged in the acknowledgments section of the manuscript.

Funding

This work was not supported by any funds.

Author Contributions

Ali H. Wheeb, the sole author of this article, has made comprehensive and in-depth contributions to its completion. He was responsible for the conception, writing, and finalization of this paper. Throughout the research process, Ali H. Wheeb independently conducted the literature review, identified the research topic, collected and analyzed relevant materials, and presented innovative ideas with rigorous logic and clear expression. His efforts ensured the integrity, scientific rigor, and academic value of this article.

Conflict of Interest

The author declares no conflict of interest.

Data Availability Statement

Data supporting these findings are available within the article or upon request.

- *Institutional review board statement*: Not applicable.
- *Informed consent statement*: Not applicable for studies not involving humans.
- *Sample availability*: The authors declare that no physical samples were used in this study.
- *Supplementary materials*: Not applicable.

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