

Routing Protocols in FANETs with Future Enhancements

Prachi Dev^{1*}, Neeta Singh²

Abstract

Flying Ad Hoc Networks (FANETs), which are swarms of Unmanned Aerial Vehicles (UAVs), are an emerging solution which revolutionized the area of mission-critical and infrastructure-less communication systems. These networks provide real-time data transfer for use cases such as disaster relief, battlefield observation, environmental monitoring, and 6G-based smart cities. However, the dynamic profile of FANETs, which is defined by high 3D mobility, limited energy resources, unstable wireless links, and constant topology changes, heavily challenges conventional routing protocols. Traditional mechanisms such as AODV, DSDV, and OLSR are unable to handle such scenarios due to their centralized or fixed nature. The latest intelligent methods, such as Q-learning-based Smart Clustering Routing (QSCR) and Deep Evolutionary Multi-Agent Deep Deterministic Policy Gradient (DE-MADDPG), have enhanced scalability and energy efficiency. However, they continue to lag in terms of convergence delays and adaptability in high-density or topologically heterogeneous environments. This study presents an intelligent routing architecture blending Federated Learning (FL), Graph Neural Networks (GNNs), Hierarchical Reinforcement Learning (HRL), and Reconfigurable Intelligent Surfaces (RIS) to build a scalable, energy-efficient, and adaptive FANET setting. Our combined approach utilizes decentralized training to maintain privacy and minimize communication overhead, an RIS protocol to enhance link quality, and HRL-aided clustering for efficient decision-making. Simulation and comparative analysis with baseline protocols validate the performance of this model against important metrics like packet delivery ratio, routing overhead, and energy consumption. This research contributes to the state-of-the-art of FANET routing by integrating several AI-based and communication-boosting technologies into one, providing a forward-compatible template for the UAV network design of a next-generation aerial system.

Keywords: FANETs, UAVs, AODV, DSDV, OLSR, QSCR, DE-MADDPG, RIS, GNN, HRL

INTRODUCTION TO FANETs

FANETs are an advanced subcategory of wireless communication networks in which a group of UAVs provides a decentralized, self-organizing aerial communication system. FANETs play a vital role in applications that demand instant deployment and real-time communication, including disaster management, military surveillance, border patrols, precision agriculture, and smart cities empowered by 6G.

FANETs are distinct from other traditional ad hoc networks such as MANETs and VANETs because they work in three-dimensional space, there is high-speed mobility, and the topology constantly changes. These create new challenges in the form of intermittent connectivity, energy limitations, low-latency requirements, and signal weakening due to environmental conditions.

To overcome these challenges, researchers are increasingly resorting to intelligent, adaptive, and

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decentralized designs. Advances in Artificial Intelligence (AI), Edge Computing, and programmable wireless systems over the recent past have made more secure and scalable FANET frameworks possible.

Characteristics of FANETs

FANETs have unique features that differentiate them from conventional MANETs and VANETs. These are caused by the deployment of UAVs as self-sustaining mobile communication nodes traversing three-dimensional airspace. Understanding these aspects is essential for formulating effective, adaptive, and scalable routing, clustering, and communication protocols for high-mobility aerial networks:

- *3D Space Mobility*: UAVs have higher mobility in 3D space (both horizontal and vertical) at much faster rates than terrestrial nodes. This poses problems in sustaining stable connections and the current routing tables.
- *Fast and Intermittent Topology Changes*: Topology changes rapidly in the network because nodes move often. Routes established at one instant might get invalid within a few seconds, requiring highly adaptive and predictive routing protocols.
- *Limited Range of Communication and Intermittent Links within UAVs*: They often operate beyond LoS, particularly in environment with physical obstacles or at different altitudes. This results in intermittent and unreliable communication links, which complicate the consistency of data delivery.
- *Power and Resource Limitations*: UAVs are powered by batteries and possess limited onboard computing and storage capacities. Energy-efficient transmission and lightweight protocols are necessary to prolong operating times.
- *Decentralized and Distributed Control*: FANETs typically do not have a static infrastructure or centralized control node. This necessitates decentralized coordination, localized decision-making, and self-organizing network behaviours to maintain performance and reliability.

These characteristics demand specialized routing architectures that are capable of dynamically adjusting to the topology changes, optimizing energy consumption, and coping with communication loss while being real-time responsive.

CHALLENGES AND LIMITATIONS OF FANETs

FANETs, comprising UAVs that dynamically form self-organizing and infrastructure-less communication networks, have demonstrated remarkable potential in domains such as disaster recovery, surveillance, environmental monitoring, and next-generation smart cities. However, despite their applicability and versatility, FANETs face a range of intrinsic challenges and limitations that hinder their performance and deployment at scales which are as follows:

- High Mobility and Dynamic Topology;
- Energy Constraints and Power Efficiency;
- Scalability and Coordination;
- Link Stability and Signal Degradation;
- Lack of Topology-Aware Intelligence; and
- Absence of Federated Learning and Privacy Preservation.

MOTIVATION FOR INTELLIGENT ROUTING IN FANETs

As the dependency of UAV swarms on mission-critical applications such as disaster response, live surveillance, environmental monitoring, and 6G-based smart infrastructure, continues to grow, so has there been a parallel growth in the need for reliable and adaptive routing protocols in FANETs. Unlike their ground-based counterparts, FANETs are characterized by their high-speed three-dimensional mobility, unstable topologies, constrained energy resources, and volatile connections. Classic routing protocols such as DSDV, AODV and OLSR known to work well in MANETs and VANETs, lack efficiency in FANET's rapidly evolving and resource-scarce aerial environments [1–3]. The proactive or reactive nature of the protocols causes unnecessary control overheads and are unable to

deal with quick topology changes efficiently. Recent learning-based solutions such as QSCR and DE-MADDPG have been introduced to overcome such problems [4, 5]. Although QSCR supports energy-efficient clustering and greater packet delivery rates, it is non-convergent under high-density networks and is not topologically universal. In an effort to fill this gap, many next-generation technologies have been incorporated into FANET systems. These include beamforming for enhanced signal reflection and power, RIS for signal boosting, and energy-restricted multihop routing to conserve energy in data transmission [6]. Also, utilization of FL supports decentralized training of models with data privacy and communication overhead minimization. Utilization of GNNs and HRL supports scalable decision-making at the routing stage with network topology awareness and energy dynamics [7–9]. The proposed routing structure builds upon an intelligent, power-aware, and very decentralized FANET ecosystem that can be structured into three conceptual layers, as depicted in Figure 1, highlighting the interactions among the UAVs, the interactions between the ground stations, and the interactions with cloud infrastructure.

Layer 1: UAV Layer (Flying Nodes)

The UAV layer is the core element of the FANET structure and is comprised of several Unmanned Aerial Vehicles (UAVs), also known as flying nodes. The UAVs operate in swarms or dynamically created clusters, depending on the network topology and mission requirements. Wireless transceivers, onboard processing units, and routing are installed within each node for multi-hop communication support. In contrast to fixed networks, this layer creates an infrastructure-free, deployable in minutes aerial communication backbone that allows real-time data exchange among UAVs. The UAV layer provides adaptive mobility, peer-to-peer local decision-making, and short-range connectivity, which are critical for applications such as disaster recovery or military missions in remote or hostile regions.

Layer 2: Base Station Layer (Ground Communication)

This middle layer is a bridge between air swarm and ground-based systems. Ground control stations, mobile base units, or roadside units make up this layer and provide support for UAV surveillance, path updates, and ground coordination. It enables UAVs to connect to the Internet, command centres, or edge computing nodes, with seamless integration with broader networks. This layer usually accommodates medium-distance communication technologies such as LTE, Wi-Fi, or mmWave links in a bid to provide high-speed data transfer rates and low latency. It also plays a key role in the implementation of handoff strategies and Quality of Service (QoS) in rapidly changing aerial conditions.

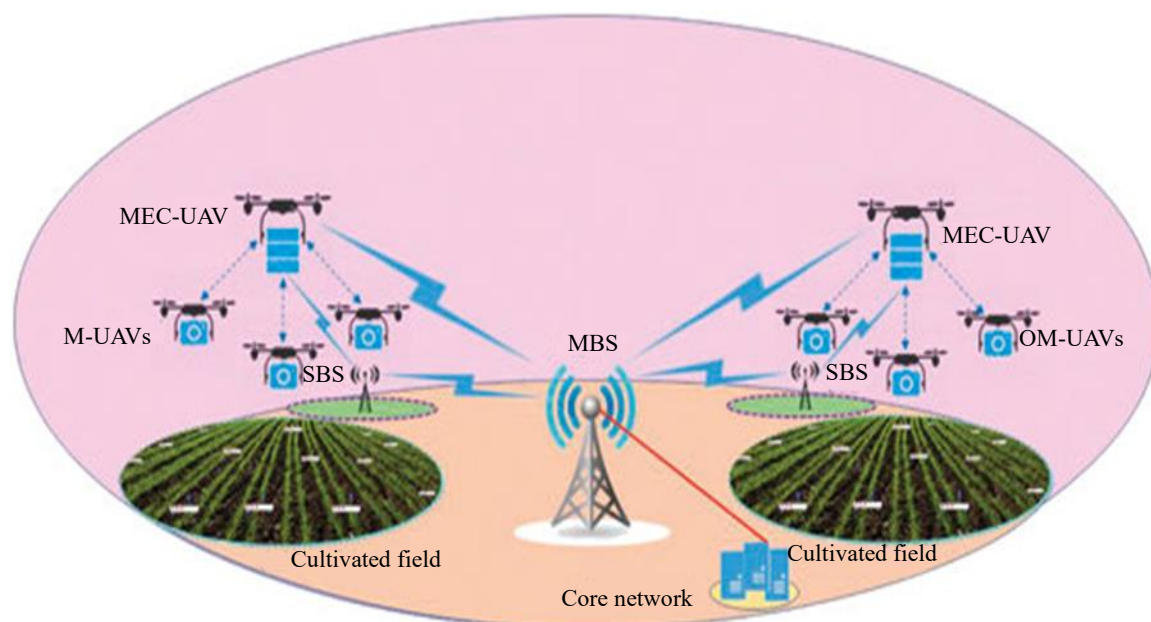


Figure 1. Layered architecture of FANETs.

Layer 3: Cloud Layer (Data Processing and Control)

Top-level cloud layer is responsible for high-level data aggregation, mission planning, control logic, and long-term storage. Sensor data, UAV location data, and real-time video streams are transmitted to cloud servers for centralized processing. This layer enables high-end applications like predictive analytics, mission optimization based on AI models, and coordination of various UAV swarms. It also makes management of the resources easier and enables integration of Digital Twins for simulation scenarios. The cloud layer is typically interoperating with 6G and edge AI infrastructure in an effort to deliver low-latency control and scale-spanning collaborative decision-making.

IDENTIFIED RESEARCH GAPS IN EXISTING FANET PROTOCOLS

While meaningful progress has been made toward designing routing protocols for FANETs, various critical research areas still hinder their practical applicability and large-scale deployment. Most of the classical protocols were initially developed for MANETs and VANETs, which are two-dimensional low-mobility scenarios. These cannot be directly projected to the three-dimensional high-mobility scenario of FANETs, and therefore performance bottlenecks and higher vulnerability to communication disruption occur.

- *Limited Flexibility to 3D Mobility:* The majority of existing protocols have poor support for dynamic 3D aerial topologies. They lack resilience against the rapid positional changes and altitude modifications typical of UAV flight [10]. For this reason, routing paths easily become outdated, leading to packet loss and communication latency.
- *Power-Hungry Routing:* Routing protocols typically involve too much control overhead, too many route discoveries, or too many redundant broadcasts, which thoroughly deplete the UAVs' scarce batteries. Prolonged flight time without power saving translates to less mission time and network instability.
- *Learning Capacity Limitation:* Most traditional as well as even recent machine learning-based protocols are plagued by a generalization problem. Flat models of learning and static routing schemes cannot learn from past network patterns or respond to upcoming mission goals and traffic demands.
- *Latency and Delayed Convergence:* Most of the centralized or semi-centralized approaches incur latency owing to the long-distance coordination and delayed feedback loops. Even some reinforcement learning approaches demonstrate slow convergence rates in dense or extensive FANETs, impacting real-time responsiveness.
- *Non-Integration Between Technologies:* A separate investigation has been conducted for individual technological innovations such as RIS, Federated Learning, and GNNs, but not many routing structures utilize the synergy of these technologies. FANETs' intelligent and autonomous features are underutilized without cross-layer integrated techniques.
- *Lack of Proper Privacy and Security Practices:* Decentralized data transmission in FANETs could impact privacy but there are no federated or encrypted learning models in the majority of protocols to protect sensitive mission information while training models or updating routes.
- *Scalability Issues:* With an increased number of UAVs, most current protocols are hampered by performance deterioration due to routing table overflow, higher collisions, and insufficient coordination. Proper clustering, role hierarchies, or load balancing procedures are normally not well established.

These knowledge gaps capture the clear necessity for an integrated, learning-capable, and energy-aware routing paradigm for FANETs. The study introduces the iQSCR-DE-MADDPG framework that addresses these limitations by integrating intelligent clustering, RIS-assisted link recovery, decentralized federated learning, and GNN-based routing to provide resilient, adaptive, and scalable performance in future aerial networks.

FUTURE SCOPE AND REAL-WORLD APPLICATIONS

The continuous advancement in FANET technologies opens up numerous research and real-world deployment prospects. With shrinking sizes of UAV equipment, diminishing energy efficiency, and

becoming cost-effective, FANETs have the potential to transform use cases that demand instant deployment, autonomous coordination, and real-time data exchange. In the near future, integration with 6G and beyond will enable FANETs to attain ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC), empowering aerial systems to become intelligent and autonomous.

Some real-world applications include large-scale deployment across disaster zones for damage evaluation and survivor localization via edge AI processing onboard drone platforms. In tactical scenarios, FANETs can form secure self-healing mesh topologies to provide connectivity within communication-denied environments. In agriculture, UAV swarms can collaboratively monitor crop health and conduct precision interventions, optimizing resource utilization and yields. Some of the newer areas in which FANETs can be integrated with IoT infrastructure are urban air mobility (UAM) and smart city surveillance for traffic management, crowd monitoring, and pollution tracking.

From the research point of view, the future can be invited to investigate meta-learning deployment for fast policy adaptation, federated reinforcement learning for privacy-driven update, and RIS-amplified MIMO methods for link reliability. Moreover, UAV-to-UAV blockchain authentication formalization and multi-agent coordination through game theory can improve the trustworthiness and autonomy of FANETs. All these make FANETs a rich soil for innovation in AI, wireless communication, and distributed computing.

CONCLUSION

The existing literature's protocol categories, organizational structures, architectural models, and communication layers all show clear deficiencies in managing dynamic, large-scale, and intelligent FANETs. Conventional protocols are incapable of managing 3D mobility, limited energy sources, and coordination of scattered aerial nodes, particularly for mission-critical or real-time communications. The above challenges illustrate the imperative of integrating intelligent, adaptive, and privacy-friendly routing paradigms that can be customized to accommodate the special requirements of FANETs.

The iQSCR-DE-MADDPG model proposed in this study addresses the above issues by including learning-based routing employing Deep Evolutionary Multi-Agent DDPG, federated model training employing Federated Learning, and smart communication enhancement employing Reconfigurable Intelligent Surfaces. Graph Neural Networks also support topologically informed routing, whereas Hierarchical Reinforcement Learning helps scalable energy-efficient clustering. This cooperative platform not only minimizes latency and control overhead but also maximizes network lifetime and packet delivery reliability.

With the integration of sophisticated technologies, this book advocates the development of future-proof FANETs with varying node densities, mission requirements, and environmental conditions. The framework unleashes opportunities for revolutionizing reality-based aerial networking systems that demand autonomy, scalability, and resilience.

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