

Flying Ad-hoc Network (FANET) Technology Innovations and Challenges: A Review

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Abstract

Flying Ad-hoc Networks (FANETs), formed by collaborating unmanned aerial vehicles (UAVs), have emerged as a promising paradigm for enabling dynamic, infrastructure-free wireless communication in three-dimensional (3-D) aerial environments. This paper reviews the state-of-the-art in FANET research, covering its architecture, communication technologies, routing strategies, recent innovations, and open challenges. Key enabling technologies such as low-power wide area wireless protocols, machine-learning based routing, and clustering algorithms are examined. We also highlight significant limitations—including high mobility, rapid topology changes, limited energy resources, and security threats—that hinder reliable large-scale deployment. The review concludes by identifying possible future research directions to overcome these challenges and fully realize the potential of FANETs across civilian, industrial, and military applications.

Keywords: FANET, UAV, ad-hoc network, routing protocol, mobility model, energy efficiency, security, clustering, machine learning.

1. Introduction

In recent years, the rapid advancement and accessibility of unmanned aerial vehicles (UAVs) have significantly expanded their use across diverse application domains, including surveillance, environmental sensing, disaster management, communication relaying, agriculture, and logistics. While single UAVs can perform many tasks, the growing demand for large-scale, persistent, and coordinated operations has shifted attention toward UAV swarms, where multiple aerial nodes operate collaboratively to improve coverage, reliability, redundancy, and overall mission efficiency. As noted by Gupta et al. (2016), coordinated UAV systems outperform individual UAV platforms by offering enhanced spatial reach and fault tolerance in dynamic environments [12]. However, enabling seamless cooperation among multiple UAVs requires a communication framework capable of coping with high mobility, frequent topology changes, and limited onboard resources.

Conventional infrastructure-based or static wireless networks are inadequate for UAV swarm operations due to their dependence on fixed base stations and their inability to adapt to rapidly changing aerial network conditions. To overcome these limitations, researchers introduced the concept of the Flying Ad-Hoc Network (FANET), in which UAVs form a self-organized, decentralized network without relying on terrestrial infrastructure. Bekmezci et al. (2013) were among the first to formally define FANETs and distinguish them from Mobile Ad-Hoc Networks (MANETs) and Vehicular Ad-Hoc Networks (VANETs), emphasizing the unique challenges posed by 3-dimensional mobility, higher velocities,

dynamic topology variation, and strict energy constraints inherent to aerial platforms [1]. Subsequent studies, including those by Hasan et al. (2024) and Hardjawana and de Freitas (2022), further highlighted that FANETs represent a distinct networking paradigm requiring tailored communication models, routing protocols, and mobility-aware designs to ensure network stability and mission success [3], [8].

Given the increasing research interest and technological advancements, it is essential to synthesize existing findings and identify gaps that remain unaddressed. Therefore, this paper presents a comprehensive review of FANET technologies, covering architectural characteristics, enabling wireless communication mechanisms, mobility and routing strategies, emerging innovations, and the major limitations that challenge real-world deployment. By integrating insights from contemporary studies, this review aims to provide a holistic understanding of FANET developments and highlight promising directions for future research.

2. Literature Review

The foundational work on Flying Ad-hoc Networks (FANETs) is presented by Bekmezci et al. (2013), who provided the first comprehensive survey distinguishing FANETs from MANETs and VANETs, highlighting their unique characteristics, communication requirements, and challenges associated with high mobility, 3-D movement patterns, and fast-changing topologies [1]. Their study established the conceptual basis for subsequent research into network models, routing strategies, and application domains. Building on this foundation, more recent studies have expanded the scope and depth of FANET research. For example, Bhatia et al. (2024) offered an updated and extensive review covering FANET classifications, architectural models, mobility patterns, communication technologies, routing approaches, and open research issues relevant to modern UAV systems [2]. Similarly, Hardjawana and de Freitas (2022) presented a detailed examination of FANET characteristics, operational scenarios, and wireless technologies, while also exploring how UAV categories influence communication constraints and routing behavior in aerial networks [3].

In the domain of routing, a significant body of work examines the limitations of traditional MANET/VANET protocols when applied to FANETs. Khan et al. (2019) and Oubbati et al. (2017) analyzed routing schemes and position-based strategies, emphasizing the challenges posed by rapid topology variations, link instability, and low node density in aerial environments [14], [15]. The survey by Lakew et al. (2020) further classified FANET routing protocols based on topology, position-awareness, and swarm coordination, stressing the need for lightweight and mobility-resilient algorithms [13]. A more recent systematic review by Jolimbetova et al. (2025) categorized routing techniques into topological, geographic, cluster-based, opportunistic, and intelligent (AI-driven or bio-inspired) families, identifying research gaps in energy-efficient routing, stability under extreme mobility, and reinforcement learning-enabled adaptation [4]. Complementary to this, Wheeb (2024) evaluated topology-based routing approaches under different FANET mobility scenarios, reinforcing the need for protocols that can withstand frequent link disruptions and altitude variations [5].

Emerging technological innovations have also gained significant research attention. For instance, Paredes et al. (2023) examined the integration of LoRa-based LPWAN technologies into FANETs, demonstrating how low-power, long-range communication can benefit energy-constrained UAV platforms and extend operational coverage [7], [16]. In parallel, bio-inspired algorithms have been explored to enhance routing reliability and energy efficiency. Lansky et al. (2023) proposed a Firefly Algorithm-based routing mechanism that selects stable multipoint relays (MPRs) using metrics such as residual energy,

neighborhood density, and link quality, showing superior performance in highly dynamic aerial conditions [6], [17]. Beyond routing and communication technologies, broader reviews such as those by Hasan et al. (2024) and Abdi (2019) discussed FANET applications, communication challenges, architectural constraints, and future directions for resilient UAV networking [8], [9]. Earlier foundational discussions by Guillén-Pérez and Cano (2018) also emphasized the importance of specialized communication models and cross-layer optimization for enhancing FANET performance [10].

Collectively, these studies illustrate the significant evolution of FANET research—from fundamental architectural understanding to advanced routing optimization, AI-driven adaptation, and integration with emerging wireless technologies. At the same time, they consistently highlight persistent challenges such as energy limitations, fast topology variation, security threats, and the need for more realistic mobility and channel models. These issues continue to shape current research directions and motivate innovations aimed at improving the scalability, robustness, and reliability of FANET deployments.

3. FANET Architectural Overview

A typical FANET comprises multiple UAVs (flying nodes) that communicate in a decentralized ad-hoc manner. The general architecture spans several layers (physical, MAC, network/routing, transport) and sometimes cross-layer designs.

3.1 Comparison with MANET & VANET

Although Flying Ad-Hoc Networks (FANETs) share certain conceptual foundations with Mobile Ad-Hoc Networks (MANETs) and Vehicular Ad-Hoc Networks (VANETs), they differ substantially in several critical dimensions. One of the most distinguishing factors is mobility: UAVs in a FANET operate in three-dimensional space and often move at higher speeds, resulting in rapid and unpredictable changes in network topology. Additionally, FANETs typically exhibit lower and more variable node density compared to terrestrial networks, as UAVs may be widely dispersed depending on the mission dynamics and operational requirements. The communication environment in FANETs is also notably different, as aerial links must account for unique radio propagation characteristics, altitude variations, directional versus omnidirectional antenna alignment, and intermittent connectivity caused by motion or environmental interference. Moreover, energy constraints are markedly more stringent in FANETs due to the limited battery capacity of UAV platforms, making energy-efficient communication and routing strategies far more critical than in conventional ad-hoc networks.

3.2 General Architecture Components

As illustrated in Figure 1, a typical FANET architecture comprises several core components that enable seamless aerial communication and coordination among UAVs. The primary elements are the UAV nodes themselves, which are equipped with wireless transceivers, sensors, communication modules, and in many cases onboard computational units that support real-time processing and decision-making. In addition to airborne nodes, a Ground Station or Control Station may be included to assist with mission coordination, data aggregation, or interfacing with terrestrial communication systems. However, in many operational scenarios FANETs function in a purely decentralized, peer-to-peer manner without relying on ground infrastructure.

The communication framework within a FANET spans multiple layers, including the physical layer responsible for radio propagation and antenna characteristics, the MAC layer managing channel access and medium coordination, the network or routing layer handling path selection and topology management, and the transport layer ensuring reliable data transmission. In some advanced designs, cross-layer

optimization is employed to enhance performance under dynamic aerial conditions. Furthermore, FANET architectures incorporate a mobility and positioning subsystem that supports UAV localization, trajectory planning, and mobility modeling. These functions are essential for maintaining network stability, improving link reliability, and ensuring effective integration of mobility patterns into routing and resource management.

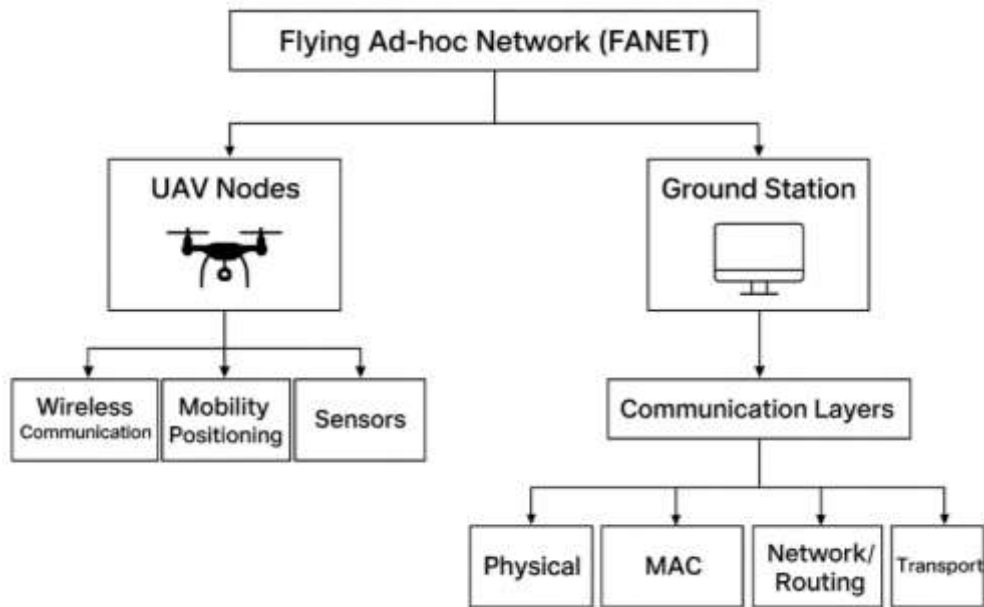


Figure 1: FANET Architectural diagram

3.3 Important Mathematical Models and Performance Metrics in FANET

1. Free-Space Path Loss (FSPL): It is used in Aerial Communication

$$FSPL(d) = 20\log_{10}(d) + 20\log_{10}(f) + 32.44 \quad \text{-----(1)}$$

2. Link Expiration Time (LET) – For Route Stability Prediction: It is Important for high-mobility FANET routing

$$LET = \frac{-(ab+cd) + \sqrt{(a^2+c^2)R^2 - (ad-bc)^2}}{a^2+c^2} \quad \text{-----(2)}$$

Where:

- $a = v_i \cos \theta_i - v_j \cos \theta_j$
- $c = v_i \sin \theta_i - v_j \sin \theta_j$
- $b = x_i - x_j$
- $d = y_i - y_j$
- r is transmission range

3. Received Signal Strength (RSS): It is important for cluster-head selection & link-quality routing

$$RSS = P_t P_r - FSPL(d) \quad \text{-----(3)}$$

Where P_t = transmitted power.

4. Signal-to-Noise Ratio (SNR): It is used to Determines reliability of aerial wireless links.

$$SNR = \frac{P_r}{N_0} \quad \text{-----(4)}$$

5. Packet Delivery Ratio (PDR): It is a most standard performance metric in FANET simulations.

$$PDR = \frac{P_{rcv}}{P_{sent}} \times 100\% \quad \text{-----(5)}$$

6. End-to-End Delay (E2E): Evaluates latency in highly mobile networks.

$$D_{avg} = \frac{1}{N} \sum_{i=1}^N (t_{recv_i} - t_{sent_i}) \quad \text{-----(6)}$$

7. Routing Overhead (ROH): It is important for FANETs because routing control cost increases greatly with mobility.

$$ROR = \frac{C_{control}}{C_{data}} \quad \text{-----(7)}$$

8. Energy Consumption Model for UAV Communication: It is used to measure energy per transmission because UAV battery is limited and energy-aware routing is trending

$$E_{tx}(k, d) = kE_{elec} + k\epsilon_{amp}d^\alpha \quad \text{-----(8)}$$

9. UAV Mobility Model – Kinematic Equations: It Helps simulate FANET 3-D mobility

$$x(t) = x_0 + v \cos(\theta)t \quad \text{-----(9)}$$

$$y(t) = y_0 + v \sin(\theta)t \quad \text{-----(10)}$$

$$z(t) = z_0 + v_z t \quad \text{-----(11)}$$

10. Network Throughput: used as Standard efficiency metric

$$Throughput = \frac{\text{Total Data Received}}{\text{Time}} \quad \text{-----(12)}$$

4. FANET Technologies

Modern FANET research leverages a variety of communication, networking, and system-level technologies to meet its unique demands. Key technologies include:

- **Wireless communication technologies and protocols:** Recent work has explored integration of low-power wide-area network (LPWAN) protocols, such as LoRa, to enable long-range, energy-efficient aerial communication—particularly beneficial where UAVs are deployed for monitoring or data collection over large areas.
- **Routing protocols tailored to FANETs:** Given the high mobility and dynamic topology, FANET-specific routing strategies have been developed. These include adaptations of traditional proactive/reactive protocols, cluster-based routing, hierarchical routing, and more recently bio-inspired and AI-driven routing schemes.
- **Clustering and hierarchical organization:** To manage scalability and resource limitations, clustering techniques are used, where selected UAVs act as cluster-heads or multipoint relays (MPRs) to coordinate communication within a group. For example, the Firefly Algorithm selects MPRs based on residual energy, connection quality, neighborhood degree, and willingness.
- **Mobility models & trajectory planning:** Realistic UAV mobility models (group mobility, leader-follower, path-based, random, etc.) help in simulation and planning; these influence connectivity, routing stability, and network performance.
- **Integration with emerging network paradigms:** Recent studies discuss combining FANETs with cloud/fog/edge computing, IoT ecosystems, and cellular or hybrid networks-aiming to expand their capabilities for data processing, storage, and reliable communication.

5. Innovations and Emerging Trends in FANET

As FANET research continues to evolve, several notable innovations and emerging trends have begun to

shape the future of aerial networking. One significant advancement lies in the development of energy-aware and bio-inspired routing protocols, where algorithms such as the Firefly-based approach have demonstrated improved route stability and enhanced energy efficiency by intelligently selecting multipoint relays based on residual battery levels, link quality, and neighborhood characteristics. In parallel, machine learning-driven strategies have gained considerable momentum, particularly those employing data-driven connectivity prediction. For instance, recent work utilizing Koopman operator theory has shown promise in forecasting link conditions, such as signal-to-interference-plus-noise ratios and potential network isolations, enabling proactive transmission scheduling and paving the way for AI-adaptive routing in highly dynamic aerial environments.

Another growing trend is the advancement of clustering and multi-hop clustering schemes, designed to ensure stable and energy-efficient communication within UAV swarms. Techniques proposed in contemporary studies emphasize selecting cluster heads based on energy reserves, mobility stability, and local node density, often complemented by ground-station-assisted maintenance to enhance cluster longevity. Additionally, hybrid communication technologies, particularly the adoption of LPWAN standards such as LoRa, are becoming increasingly attractive for FANET applications requiring extended communication ranges and low power consumption, such as IoT-driven sensing or ground-to-air data exchange. Beyond this, researchers are exploring cross-layer and heterogeneous networking approaches that integrate FANETs with terrestrial wireless systems, IoT infrastructures, cellular networks, and cloud/fog/edge computing platforms. These integrations aim to expand network functionality, improve reliability, and support more sophisticated real-time applications.

Collectively, these advancements signal a shift away from traditional MANET-inspired adaptations toward highly specialized, intelligent, and resource-efficient solutions tailored to the unique demands of UAV swarms operating in dynamic 3D environments.

6. Challenges and Limitations in FANET

Despite substantial progress, FANETs face many intrinsic and practical challenges that hinder their widespread deployment. Key challenges include:

- **High mobility and frequent topology changes:** UAVs move unpredictably in three dimensions, often at high speeds, causing rapid changes in network topology and frequent link breakages. This complicates routing, leads to instability, and reduces reliability.
- **Energy constraints:** UAVs typically rely on limited onboard battery power; communication, sensing, and flight all consume energy. Energy-aware protocols and efficient clustering/routing are crucial — yet many existing solutions optimize only limited aspects (e.g., route stability, throughput), often neglecting power consumption or energy balancing.
- **Sparse node density and connectivity issues:** Depending on mission and environment, FANETs may have few UAV nodes spaced far apart, resulting in sparse connectivity, network partitions, or long communication delays. This is especially challenging when using sparse/rural deployment, wide-area surveillance, or disaster-area coverage.
- **Communication reliability and propagation challenges:** Radio propagation in aerial environments can be unpredictable. Assumptions such as isotropic or omnidirectional antennas may not hold; directional antennas, varying altitude, signal fading, interference, and mobility all influence link quality. Modeling and designing robust MAC/physical-layer solutions remains difficult.

- **Scalability and dynamic resource management:** As the number of UAVs increases, managing communication overhead, routing maintenance, clustering, load balancing, and coordination becomes complex. Efficient resource management (bandwidth, power, spectrum, computational resources) is critical but underdeveloped.
- **Security vulnerabilities:** Due to decentralized architecture and dynamic membership, FANETs are susceptible to malicious nodes, impersonation, packet dropping, routing manipulation, and other attacks. Ensuring confidentiality, integrity, availability, secure routing, authentication and intrusion detection remains an open challenge.
- **Need for specialized simulation tools and realistic mobility/propagation models:** Evaluating FANET protocols often requires realistic simulations of 3D mobility, UAV dynamics, varied communication conditions, and cross-layer interactions. Lack of standard tools and models can bias results or limit reusability.
- **Integration with other technologies and heterogeneity:** Combining FANETs with terrestrial networks, IoT, cloud/fog/edge systems, or hybrid communication means introduces complexity: interoperability, latency, variable link reliability, and resource management issues.

7. Conclusions

FANETs represent a compelling paradigm for enabling aerial, infrastructure-free, flexible, and dynamic wireless networks using swarms of UAVs. Over the past decade, considerable research has advanced our understanding of FANET architecture, characteristics, routing protocols, mobility models, and enabling technologies. Recent innovations—such as energy-aware routing using bio-inspired algorithms, cluster-based organization, machine-learning driven connectivity prediction, and integration with LPWAN or cloud-based systems—highlight the evolving sophistication of FANET research.

Nevertheless, FANETs remain challenged by high mobility, dynamic topology, energy constraints, sparse node density, communication reliability issues, security threats, scalability, and lack of standardized models or tools. Overcoming these obstacles will require holistic, cross-layer research combining advancements in communication technologies, routing and network protocols, energy management, security frameworks, and intelligent decision-making (e.g., AI/ML-based adaptive protocols).

Future research will likely focus on hybrid networking (FANET + ground/infrastructure networks), AI-driven adaptive routing & resource allocation, secure and resilient communication architecture, realistic simulation frameworks, and real-world deployment in diverse application domains (disaster response, environmental monitoring, delivery networks, IoT sensor networks).

In summary, FANETs hold significant potential to transform aerial networking and enable novel applications — but realizing that potential demands continued effort to address their inherent challenges.

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