VOL. 25, NO. 2, 2026, 99-112
elektrika.utm.my
EISSN 3083-9394

ELEKTRIKA
Journal of Electrical Engineering

Applications and Challenges of Flying Ad-Hoc Networks in Disaster Response: A Review

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Abstract: Natural disasters cause massive destruction to power infrastructure and communication networks and limit access to proper emergency response. Unmanned aerial vehicles (UAV)-based Flying ad hoc networks (FANETs) offer a useful communication layer through aerial observation, line-of-sight relay support, and cooperative multi-hop networking to restore connections in affected areas. However, the available FANET literature uses different assumptions about mobility, channel conditions, interference, traffic profiles, and performance metrics, which limits proper cross-study comparison and protocol selection for emergency use. In this review, we examine the most recent FANET architectures and disaster-response protocols, including medium access control, routing, topology management, and energy-aware operation. We also analyze connectivity-preservation strategies under rapid topology change, including mobility prediction, link-quality estimation, geographic relay selection, and control-plane design. We then evaluate the role of multi-agent reinforcement learning (MARL) in decentralized task allocation, relay selection, spectrum access, and power control under partial observability. Future research should prioritize reproducible experimental evaluation of FANET architectures, MAC protocols, routing strategies, and AI-enabled coordination under realistic disaster conditions.

Keywords: FANETs, UAV, Disaster Response, Routing Protocols, Communication Challenges

Article History: received 14 June 2025; accepted 12 June 2026; published 31 August 2026
Digital Object Identifier 10.11113/elektrika.v25n2.757

1. INTRODUCTION

UAVs support remote sensing, rapid inspection, and time-sensitive response in industrial, environmental, and public-safety missions [1]. UAV payloads, such as cameras and sensors, capture images and live video that help response teams observe areas with limited ground access or urgent coverage needs [2]. During emergency events, real-time UAV observations add a current operational layer to historical datasets, which usually receive less frequent updates. Regular evaluation of real-time UAV observations can shorten response time and support situational management, incident control measures, and operational decisions during fire and flood emergencies. UAV connectivity also allows automated transfer of sensor-output time-series data to local or cloud-managed storage systems. Automated data transfer reduces direct human intervention in data handling and helps preserve chain of custody [3].

A single-UAV mission may rely on a satellite link, ground-based station, or airborne control station. Multi-UAV missions require stronger coordination and more reliable communication [4], [5]. Flying ad hoc networks (FANETs) address multi-UAV communication demands through decentralized topologies, where each drone acts as an autonomous node that supports core network services as well as sensor acquisition, communication, and computation capabilities [6]. Distributed UAV roles allow cooperative missions to continue without full dependence on a central controller.

Decentralized UAV operation also enhances resilience when a UAV node fails or link quality deteriorates. In wide-area missions, small-UAV swarms offer practical advantages over a single large UAV, including broader coverage, redundancy in the event of node failure, and parallel task execution [7]. FANET operation imposes design requirements that differ from many traditional ad hoc networks as low network density, rapid topology variation, and high node velocity shape link stability and routing performance. Figure 1 shows a representative flying ad hoc network topology [8].

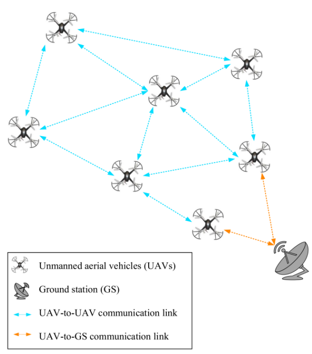

Figure 1. FANETs topology [8].

FANET-enabled UAV swarms support missions across military and civilian domains. Public safety support, search and rescue, reconnaissance, border surveillance, autonomous target pursuit, fire response, internal security operations, wind estimation, remote observation, traffic surveillance, and relay networks represent common mission categories. Civilian adoption also spans transportation services, internet parcel delivery, architecture and infrastructure inspection, film production, and agricultural surveillance [9], [10], [11], [12].

FANETs also represent an effective instrument for enhancing fifth-generation (5G) network architecture. Structural limitations of UAV devices remain significant, and restricted onboard computation and limited energy must supply propulsion, sensing payloads, and onboard processing, but multi-UAV cooperation still supports complex mission objectives under these constraints. A 5G infrastructure perspective also benefits from UAV-provided ubiquitous connectivity and edge computation for device types that operate in remote or underserved regions, and aerial platforms support temporary service restoration after infrastructure disruption [13], [14], [15].

UAVs have become a crucial component in modern communication, particularly within Space-Air-Ground Integrated Networks (SAGINs). UAV mobility, flexibility, and rapid deployment support time-sensitive missions, yet operational constraints still limit performance under mission-critical requirements. The high velocity of UAV platforms causes frequent topology changes; in turn, dynamic topology variation disrupts stable route formation and reliable link schedules over time.

Long-range operations add further constraints because bandwidth stays limited and end-to-end latency increases when traffic must pass through multiple hops across wide disaster areas. Energy availability is another limitation as battery replacement or field recharge is not feasible during active missions.

Security risk can also be high because exposed wireless links allow interference attacks, node spoofing, and data tampering, especially during sensitive operations. System heterogeneity adds another layer of difficulty because the integration of UAVs, protocols, and network components from different sources can reduce compatibility, disrupt synchronization, and complicate resource management.

Moreover, many existing UAV communication studies rely mainly on simulation, which limits confidence in how protocols can perform under real ad hoc conditions with unpredictable dynamics and hardware imperfections. Consequently, effective deployment in mission-critical environments requires unified operational designs that combine reliability, energy efficiency, security, and seamless cross-network connectivity. Multi-UAV cooperation can enable completion of complex mission tasks despite structural device limitations, such as limited energy available to supply engines and computing elements, and limited computing capabilities [16], [14]. A 5G infrastructure can also benefit from UAV-provided ubiquitous connectivity and computation for device types located remotely, such as rural agricultural systems that require wide-area coverage and resilient communication links under sparse terrestrial service [17].

The review is organized as follows: Section 2 presents a comprehensive literature review on FANETs and related technologies. Section 3 provides a comparative analysis of FANETs, MANETs, and VANETs and discusses the architecture of FANETs. Section 4 explores the FANET communication layers, including physical and data link layers, and routing protocols. Section 5 discusses disaster application areas for FANET deployment, and Section 5 covers fire hazards, floods, and earthquakes. Section 6 identifies major challenges that affect FANET deployment in disaster response. Section 7 presents AI integration in disaster-resilient FANETs. Section 8 provides the conclusion and outlines future research directions.

2. KEY CONTRIBUTIONS

The motivation for the present review arises from the limited coverage of FANET architecture in the current literature and the fragmented discussion of disaster-response protocol requirements. Disaster-response missions impose extreme operational demands, and a useful evaluation of FANETs therefore requires a connected view of network architectures, protocol layers, and routing families. The review addresses FANET application in disaster response by examining studies related to fire hazards, floods, and earthquakes. The relevant literature is organized according to mission objectives, network assumptions and reported performance metrics in the discussion. The review also addresses the application of MARL for decentralized task allocation, relay selection and resource control in dynamic environments. Finally, we present some of the key challenges and research opportunities including management of FANETs, their online adaptation under partial observability, the security assurance ensuring resilience against cyberattacks, along with field validation.

3. LITERATURE REVIEW

The use of FANETs is a fast growing research area in wireless communication network, where numerous investigations have been proposed. Most of the studies propose strategies that improve network performance, refine routing algorithms, and integrate emerging technologies into FANET operation. At the same time, real-time deployment is elusive. Table 2 summarizes representative reviews and reports their focus areas and contributions.

Table 2. Related work

Ref.	Focus	Main Insight	Limitations
[18]	Review of FANET Routing Strategies	FANET routing protocols address mobility and topology challenges	No experimental/simulation data; purely theoretical.
[19]	Review of FANET and AI in Disaster Management	FANETs and AI are vital for disaster management, but face research gaps	FANET challenges in disasters are underexplored.

		and technical challenges.	
[20]	Review of FANET Mobility Models for Disaster Areas	Effective mobility models and optimized networks enhance FANET applications in disaster management.	Focuses only on existing mobility models
[14]	Review of UAV Disaster Scenarios in a Smart City	UAVs and 5G enable efficient disaster management with optimized path planning, addressing urban and network challenges.	Focuses mainly on the post-disaster phase

4. COMPARISON OF MANETS, VANETS, AND FANETS

Wireless networks have developed rapidly in recent years, and their development has opened the door to many services across different application domains. Modern wireless systems also use multiple frequency bands, which allows more flexible access and can reduce congestion when spectrum use is planned well.

Wireless Ad Hoc Networks (WANETs) form a network class that operates without central control nodes, where all nodes share similar roles within the network. Wireless mesh networks describe a closely related model, with greater emphasis on multi-hop relays and distributed connectivity. Network nodes can join or leave as operational needs change, which makes WANETs suitable for dynamic environments [21], [22].

Mobile Ad Hoc Networks (MANETs) provide the conceptual basis for FANET development because both network classes rely on self-organization, limited central control, and ad hoc operation. FANETs share MANET features that include distributed control and topology self-formation, and those features support communication expansion in unstructured areas.

FANETs also share partial similarity with Vehicular Ad Hoc Networks (VANETs) because both systems include mobile nodes operating over changing geography, which influences connectivity patterns and routing constraints [23].

FANETs share core ad hoc properties with MANETs and VANETs, yet UAV nodes operate under mobility profiles that exceed typical ground mobility, and that mobility becomes the primary differentiator for protocol design. Table 3 summarizes comparisons between FANETs, VANETs, and MANETs across key criteria [24], [25], [26], [27].

Table 3. Comparative Analysis Of Manet, Vanet, And Fanet

Parameters	MANETs	VANETs	FANETs
Node Density	Low	Medium	Very Low
Node Velocity	Low	Medium	High
Power Consumption	Energy-Efficient Consumption	Not Needed	Need for mini-UAVs
Topology Change	Slow	Rapid	Rapid
Radio Propagation	Near to Surface	Near to Surface	High Above the Surface
Mobility Model	Arbitrary	Steady	Mobility models for autonomous multi-UAV systems are typically predetermined, but exceptions apply.

5. FANET ARCHITECTURE

FANET form ad hoc communication networks through cooperation among multiple UAVs. Reliable maintenance of an air-to-air communication channel among UAV nodes represents a primary design requirement for any multi-UAV network because cooperative routing, coordination messages, and sensor-data exchange depend on persistent connectivity. Many applications rely on micro- or small UAV platforms because compact airframes allow access to confined locations that larger UAVs cannot reach, and micro-UAV platforms can also maintain hover above a defined region for sustained observation and relay service. Micro-UAV platforms also place practical limits on network architecture and hardware selection. Limited payload capacity restricts sensor size and capability, communication links constrain the operational range, and onboard power supply limits flight duration and radio service time. Therefore, the hardware selection for small UAV platforms needs lightweight components, compact form, and small power electronics sufficient to preserve endurance and maintain communication and sensor functions [28].

A functional networking architecture must support safe and consistent data exchange between UAV nodes and the base control elements involved in data transmission and mission supervision. A multi-UAV FANET often includes a designated UAV that works as a gateway between the base control element and other UAV nodes. Gateway selection can extend coverage beyond the direct base-station range and support coordination across a wider disaster area. A gateway-based model requires clear network roles, explicit network organization, and reliable communication modes that cover air-to-air and air-to-ground links under mobility. Literature sources describe similar highly mobile networking models under different terms, but the core requirement remains consistent around robust connectivity under rapid movement and frequent topology updates. UAV adoption across civilian and military fields continues to expand rapidly, and scalable FANET architectures will therefore remain central to multi-UAV mission design.

Centralized architectures can optimize network decisions when global network information is available. Centralized control, however, introduces a single-point-failure vulnerability and can cause long control-signal delays in disaster environments. Decentralized architectures provide better robustness and scalability because control functions are distributed across UAV nodes. Decentralized control, however, depends on partial information at each UAV node, and incomplete neighbourhood awareness can reduce decision-making accuracy under high mobility and intermittent link conditions. Figure 2 presents a FANET architecture that consists of satellites, Ground Control Stations (GCSs), UAV nodes, and a High-Altitude Platform (HAP) or Low-Altitude Platform (LAP) station [29].

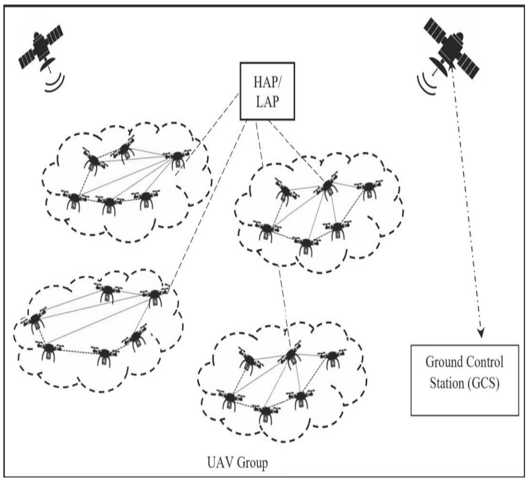

Figure 2. Fanet Architecture.

5.1 FANET Physical Layer

The physical layer of the FANET controls the signal propagation in UAV-to-UAV links and UAV-to-Base Station (BS) links. The communication distance between UAV nodes is a continuous random effect dictated by flight dynamics. Antenna design represents a primary design factor in stationary networks, since antenna characteristics directly affect the link budget, the coverage footprint, and connection reliability. Proper antenna selection is important as it influences system reliability, especially in mobility scenarios in which link margins fluctuate rapidly.

Limited transmission power make omnidirectional antennas less efficient for a specific receiver because omnidirectional radiation spreads power over a wide spatial region. Directional antennas concentrate radiated power toward a specific direction to increase the effective range and improve link quality as long as beam alignment remains stable. Directional transmission is also used to improve the signal-to-noise ratio and increase channel capacity. Higher channel capacity is particularly valuable for links with high bandwidth demand.

Multi-hop delay accumulation occurs when relays forward traffic across intermediate nodes. Relay-based communication that supports real-time applications therefore requires low packet latency at each intermediate node because accumulated delay limits practical coverage extension [30]. The following subsections describe communication technologies commonly considered for FANET systems, including WiFi, Bluetooth, ZigBee, and LTE [31].

5.1.1 WiFi (IEEE 802.11)

Wireless fidelity (WiFi) represents a short-range networking technology that uses radio-frequency communication and Wireless Local Area Network (WLAN) design guidelines. Common WiFi operating bands include 2.4 GHz, 3.6 GHz, 5 GHz, and 60 GHz. IEEE 802.11a/b/g/n/ac variants can provide the throughput required for large data transfer, such as images and video streams, across many FANET missions. A conventional WiFi link typically offers an effective transmission range of about 100 m under standard conditions [32], [28].

Ad hoc multi-hop connectivity can extend UAV broadcast coverage to several kilometres through relay-based forwarding between airborne nodes. A standard IEEE 802.11 infrastructure network uses Access Points (APs) that transmit periodic announcements, and client devices rely on those announcements to discover and join Wireless Local Area Networks (WLANs). Several studies evaluate WiFi efficiency for a UAV–GS link using Received Signal Strength Indicator (RSSI), achieved throughput, and UAV–GS separation distance. Some studies also report that an IEEE 802.11a wireless link between a UAV and GS can support FANET-based applications. Multi-band operation requires an IEEE 802.11 wireless adapter that supports multiple frequency bands, such as 2.4 GHz, 5 GHz, and 6 GHz. The WiFi Alliance introduced a numbering system that distinguishes WiFi protocol generations, which includes 802.11b, 802.11a, 802.11g, 802.11n, 802.11ac, and 802.11ax. Certain variants can operate on both 2.4 GHz and 5 GHz bands within the same device design [33]. Table 1 lists representative IEEE 802.11 standards and summarizes frequency, speed, and transmission range.

Table 1. Shows the list of WIFI 802.11n standards

IEEE Standard	Frequency/Medium	Speed	Transmission Range
802.11	2.4 GHz RF	1-2 Mbps	20 feet
802.11a	5 GHz	Up to 54 Mbps	25–75 feet; building materials can reduce range
802.11b	2.4 GHz	Up to 11 Mbps	Up to 150 feet; building

			materials can reduce range
802.11g	2.4 GHz	Up to 54 Mbps	Up to 150 feet; building materials can reduce range
802.11n	2.4 GHz/5 GHz	Up to 600 Mbps	175+ feet; building materials can reduce range
802.11ac	5 GHz	Up to 600 Mbps	175+ feet; building materials can reduce range

5.1.2 Bluetooth

Bluetooth operates in the unlicensed 2.4 GHz band and typically supports transmission ranges from about 10 m to 200 m, depending on device class, antenna characteristics, and operating environment. Bluetooth implementations provide data rates that commonly fall between 1 Mbps and 3 Mbps, while some variants report a maximum data rate of 24 Mbps. Bluetooth Low Energy (BLE) entered the Bluetooth 4.0 specification through the Bluetooth Special Interest Group (SIG), and BLE targets reduced energy consumption for short-range communication links [34].

Bluetooth 5 targets higher speed, extended transmission range, lower energy consumption, and improved coexistence with other short-range technologies. Bluetooth 5 also supports richer data exchange, which can include multimedia and URL files in addition to positioning-related information. Bluetooth 5 appears as a potential option for low-cost and low-power FANET deployment in scenarios that tolerate short-range connectivity. Some researchers describe Bluetooth-based UAV networking in a master-slave structure with one master UAV and up to seven slave UAV stations. Reported results indicate that a Bluetooth-based FANET can provide effective connectivity with negligible computational overhead [35].

5.1.3 ZigBee (IEEE 802.15.4)

ZigBee is commonly used in low-data-rate applications that require secure networking and long battery life. Typical operating range falls between about 10 m and 100 m, and ZigBee often offers lower cost and simpler deployment than WiFi and Bluetooth for low-throughput communication needs. ZigBee operates in the 2.4 GHz band and provides a nominal data rate of 250 kbps. The standard defines 16 channels, and each channel occupies 5 MHz of bandwidth. ZigBee can therefore suit low-data-rate FANET scenarios and has been used for indoor localization and intra-cluster communication within FANET deployments [36], [5].

5.1.4 Long Term Evolution (LTE)

The LTE provides high data throughput, mobility support, and reliable wireless connectivity, and these features can improve network management and security. LTE targets IP-based communication and supports scalable bandwidth options that include 20 MHz, 15 MHz, 10 MHz, and bandwidth values below 5 MHz. LTE also supports Time Division Duplexing (TDD) for unpaired spectrum and Frequency Division Duplexing (FDD) for paired spectrum. LTE cell coverage typically targets about 5 km, yet operation can remain effective within 30 km and can remain functional up to 100 km under suitable conditions. Experiments also report that FANET deployments can support live video streaming and monitoring over 4G-LTE networks [37].

5.2 Data Link Layer

The data link layer includes the medium access control (MAC) sublayer. The MAC sublayer regulates access to the shared transmission medium, which determines how multiple UAV nodes contend for the same wireless channel. Protocols proposed at this layer therefore govern management and control of the shared communication channel across all nodes, and MAC decisions affect packet collisions, retransmissions, and channel occupancy during mobility. In wireless sensor networks, MAC protocols also support self-organization by providing the coordination required for hop-by-hop wireless communication, and similar principles apply to FANET operation when multi-hop forwarding remains necessary. Key MAC protocol attributes include energy efficiency, scalability, network throughput, fairness, latency, and bandwidth utilization [38]. MAC design must therefore address issues that include energy consumption, fairness among competing nodes, link-quality variation, efficient channel utilization, and packet delay. Table 4 presents a taxonomy of MAC protocols for UAV networks.

Table 4. Fanet Mac Protocols

FANET MAC Protocols		
Contention-Free MAC Protocol	Contention Based MAC Protocols	Hybrid MAC Protocols
CU-MAC [39]	Sensor MAC [40]	LODMAC [41]
UD-MAC [42]	Time Out MAC [43]	FMAC [44]
	Pattern MAC [45]	CC-MAC [46]
	DFRA MAC [47]	CF-MAC [48]
	O-ALOHA MAC [49]	
	AO-ALOHA MAC [50]	

5.3 Routing Protocols

Researchers initially examined routing protocols from MANETs and VANETs for potential use in UAV networks because FANETs share fundamental ad hoc networking principles with those systems. FANET nodes also operate under distinctive conditions, and limited onboard energy, high mobility, and rapid link variation impose requirements that differ from many ground-based networks. Existing MANET and VANET protocols therefore require modification to satisfy FANET operational criteria. Routing protocols considered for FANETs are commonly grouped into five categories: proactive routing protocols, static routing protocols, on-demand routing protocols, hybrid routing protocols, and spatial routing protocols. Table 5 lists representative protocols within each category and summarizes reported limitations.

Table 5. Fanet Routing Protocols

Category	Protocols	Issues in Application to FANET
Proactive	P-OLSR [51] COLSR [52] DOLSR [53] MILOSR [54]	- High overhead for table updates. - Significant bandwidth consumption. - Slow topology change reaction.
Reactive	RGR [55] Time Slotted [56] RTORA [57] AODV [58]	- Large header size increases network overhead. - High latency during pathfinding. - Requires intermediate nodes for routing.
Hybrid	GPSR [59] TORA [60] ZRP [61]	- Difficult to manage in dynamic environments.
Geographic	MPGR [62] GPMOR [58] GPSR [63] LAROD [64] USMP [53]	- Node location sharing strategies may be unrealistic in some cases.
Static	MLHR [53] DCR [53] LCAD [65]	- Not scalable and unable to handle changes. - Unsuitable for dynamic FANET topologies.

Overall, proactive routing offers faster access to routes but creates high control overhead under rapid UAV mobility, while reactive routing reduces overhead at the cost of higher delay. In disaster scenarios, where topology changes frequently, neither approach is fully optimal, which suggest the need for adaptive routing mechanisms tailored to FANET environments.

6. DISASTER APPLICATION TYPES

Large-scale disasters, such as wildfires in Australia and California, earthquakes in Indonesia, and floods in Central America, have shown a higher frequency in recent years under climate-related stressors. Major disasters affect large areas and vulnerable populations. Inadequate preparedness and weak early response can lead to higher casualty rates and delayed medical aid, especially when damaged infrastructure limits access to affected communities. Public health protection and public safety improvement therefore motivate research on rapid situational awareness, resilient communication, and coordinated response systems for disaster contexts [66]. FANET-based deployments support several disaster application categories, and each category imposes distinct sensing, communication, and coordination requirements.

6.1 Fire Hazard Emergency

Fire incidents impose fast-evolving hazards, reduced visibility, and rapidly changing safety boundaries, and these conditions demand early detection, continuous perimeter mapping, and reliable communication between responders and command units. UAV swarms can support these requirements through cooperative sensing and multi-hop relays that sustain information flow when smoke, terrain, or infrastructure damage weakens terrestrial systems.

Simoes *et al.* [67] propose an aerial drone network that supports firefighting through cooperative sensing and communication. The proposed approach uses UAV sensor data to delineate the fire region, and multi-UAV cooperation forms an ad hoc network that tracks firefighter positions and forwards operational information that supports coordinated rescue actions. The same study also describes an ad hoc network that maintains hover above active firefighter teams, and network nodes adjust spatial positions based on sensed conditions to collect field data and transmit that data to a ground station.

While Bharany *et al.* [68] focus on energy-aware data delivery under emergency supervision settings and propose an energy-efficient clustering approach for sensor nodes. Cluster Head (CH) selection relies on multiple attributes that support routing within a clustered structure. The method applies the SPIHT image-compression technique to reduce transmission load, and the SRCM model supports path selection toward the destination with consideration of node energy level and communication link quality.

On the other hand, Cretu *et al.* [66] emphasize the operational value of early-phase forest fire detection for community preparedness, casualty reduction, and reduced pressure on emergency medical systems. The same work describes wildfire monitoring through networks of unmanned aerial vehicles, where ad hoc inter-UAV communication can deliver time-sensitive information that supports emergency response actions. The proposed smart architecture combines Flying Ad-Hoc Networks with fog-computing support, and the described FANET consists of UAV nodes with WiFi links that transfer data from the affected region to edge nodes, after which the fog infrastructure forwards the data to nearby facilities with response capacity.

6.2 Flood Emergency

Flood disasters often evolve across wide areas and can isolate communities through road damage, bridge failure, and power disruption, so response teams require rapid mapping, continuous observation, and reliable emergency communication coverage. UAV platforms can capture aerial imagery across inaccessible zones, and FANET connectivity can support multi-hop relay services that extend communication beyond a single UAV footprint. Munawar *et al.* [69] proposed a CNN-based deep learning approach that uses UAV aerial images as input for flood detection. UAV mobility also enabled access to confined spaces and supported image capture that clarified the flood impact on homes, complex building layouts, and critical infrastructure. The study selected CNN-based deep learning because CNN architectures often provide strong performance in image segmentation and image classification tasks.

Furthermore, Shah [70] also addressed communication continuity during flood response and proposed an emergency communication architecture that relies on a FANET instead of a single UAV. The work proposed a cluster-based method that targets communication reliability and communication efficiency (Figure 3). The work also described a cluster-management procedure that preserves the cluster structure because cluster stability supports FANET reliability.

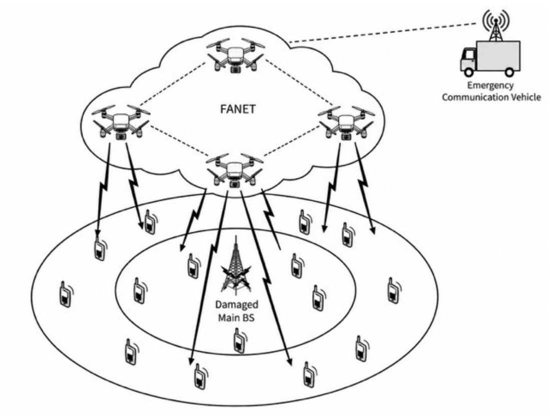

Figure 3. Emergency FANET-based communication architecture [70].

6.3 Earthquake Emergency

Earthquake response requires rapid situational awareness, scalable communication services for affected users, and resilient coordination when infrastructure collapse disrupts emergency operations. Ground BS damage can remove coverage at the moment when ground users need emergency connectivity, and damaged transport corridors can delay physical access to incident zones. UAV swarms can provide temporary communication coverage and can transport disaster information to rescue centers through multi-hop routing. Liu et al. [71] examined joint optimization of FANET network efficiency and mission efficiency in earthquake rescue scenarios. Ground Base Station damage forces UAV platforms to provide communication service to a large number of Ground Users (GUs). UAV nodes must also collect disaster information from GUs within the disaster region and forward that information to the rescue center with minimal delay because damaged ground transportation can restrict physical access and can slow information transfer.

Furthermore, Qu et al. [72] introduced an obstacle-aware and energy-efficient multi-drone coordination and networking approach that integrates a packet-forwarding algorithm with a location-aided prediction algorithm for UAV-to-ground networks in earthquake contexts. The approach uses Reinforcement Learning (RL) for trajectory prediction based on onboard sensor input and coordination-state information, and the approach targets improved coordination under obstacle constraints and energy limits. Ghosh et al. [73] also examined disaster-response workload through queueing analysis and evaluate factors that include event arrival rate during crisis periods, UAV service rate, event waiting cost, and UAV idle cost. The same work recommended an appropriate UAV fleet size for casualty reduction through queueing models such as M/M/c/K/FCFS.

7. CHALLENGES OF FANET

FANETs operate under conditions that differ from many terrestrial ad hoc networks, and high mobility, frequent topology variation, and constrained energy resources create persistent challenges for routing and communication protocols [74]. Multi-UAV cooperation introduces additional requirements, such as distributed algorithms, integrated communication and control mechanisms, and safety assurance during coordinated flight. Mission control must manage trajectory planning, collision avoidance, and coordination timing to ensure safe and effective multi-UAV operation. Distributed cooperation algorithms must also preserve UAV autonomy as they support coordination under disruptive conditions, including node failure, communication loss, hostile interference, and variable environmental constraints. Reliable deployment therefore requires careful design across network components that affect effectiveness, dependability, and security.

A network perspective on disaster monitoring and surveillance highlights challenges in communication protocols, network architecture, topology control, path optimization, fault tolerance, routing robustness, and security assurance [75]. Disasters also expose limitations of single-UAV systems as dynamic and unpredictable conditions can disrupt reliable links to the ground station, and coverage constraints can prevent adequate monitoring across large and complex disaster zones. Scalability therefore becomes a major concern, and multi-UAV systems represent a common approach for addressing coverage and connectivity requirements under disaster conditions [76].

7.1 Cyber-Physical Security

UAV networks face security threats that include jamming, malicious attacks, eavesdropping, and control-signal forgery. These threats can compromise both UAV operation and the confidentiality and integrity of mission-critical data. Recent studies have emphasized security mechanisms for UAV and FANET environments, yet practical deployment still requires clearer understanding of implementation constraints. Hardware resource requirements, processing load, and communication overhead consume payload capacity and computational resources. Additional resource demand can also reduce battery endurance and threaten mission success [75]. Future research need to evaluate security designs under realistic hardware limits and operational conditions, with explicit attention to energy cost and deployment feasibility.

7.2 Routing issues

High mobility and sparse network density in UAV operations cause rapid topology changes and frequent link disconnections, which makes routing protocol design challenging because routes may remain available for a short time. Route instability can reduce routing efficiency and degrade the overall network performance. Conventional routing schemes developed for MANETs and VANETs often perform poorly in UAV networks because UAV mobility patterns and link dynamics differ substantially from ground-based networks. Rapid platform movement also changes communication constraints during the mission.

Current FANET routing studies consider factors such as hop count, link quality, congestion state, and energy efficiency. A standard routing approach, however, has not yet integrated these factors in a unified manner and maintained low control overhead with a high packet delivery ratio during disaster scenarios. Some approaches avoid continuous route-table maintenance. Alternative mechanisms, such as SCF, can still introduce additional overhead during packet forwarding and coordination. Security risks also remain important during disaster operation because malicious replay attacks and false signaling can disrupt routing decisions and trigger mission failure even when packet delivery remains high. Many advanced protocols also depend mainly on simulation-based evaluation, and assumed mobility rates may not represent real field conditions accurately [77], [78].

7.3 Battery Power

UAV operation relies heavily on battery power, and battery dependence limits flight duration, payload operation time, and communication service continuity. Energy optimisation therefore becomes essential for missions in disaster zones and remote areas, where recharge access often remains limited and mission timing has strict constraints. AI, ML, and ANNs can support energy-aware routing and resource management. AI-based methods, for example, can adapt network decisions in real time, reduce transmit-power waste, avoid unstable links, and limit unnecessary control traffic.

Green energy options are attracting increasing attention as complementary solutions for UAV endurance improvement. Solar-assisted UAV designs use lightweight photovoltaic panels that harvest energy during flight. Solar energy support can reduce exclusive reliance on battery discharge during extended missions. Advances in hybrid power systems, battery chemistry, and efficient power electronics are expected to play an important role in improving endurance and operational efficiency across future UAV deployments [7].

7.4 Denial-of-Service and Distributed Denial-of-Service

UAV networks face Denial-of-Service (DoS) and Distributed Denial-of-Service (DDoS) attacks when defence mechanisms are inadequate. DoS attacks target network availability through excessive request volumes that congest communication links and exhaust node resources. DoS pressure disrupts mission operation through battery depletion, channel congestion, and processing-unit overload, which delay command exchange and sensor-data delivery.

Furthermore, DDoS attacks intensify the availability threat as multiple attack sources overwhelm UAV nodes and the supporting infrastructure. Coordinated DDoS traffic makes the network unreachable during critical mission phases.

Signal spoofing and command hijacking also threaten UAV navigation and command integrity. Attackers inject fabricated data into GPS channels to distort position estimates and disrupt planned routes. Moreover, command hijacking allows an adversary to send unauthorised control instructions. Weak authentication and inadequate control-channel protection can escalate command hijacking into full UAV takeover. Session hijacking threatens UAV communication because an attacker intercepts or manipulates session credentials and redirects control flows. Strong authentication, spoofing detection, signal-distortion analysis, and direction-of-arrival sensing reduce attack success probability and support early threat identification.

The compromise of GCS via malware, viruses, and keyloggers also exposes mission data and allows malicious command transmission to one or more UAV nodes. A compromised operator endpoint becomes a direct pathway for adversarial control. Malicious operational commands take control of vulnerable UAV nodes and threaten data confidentiality and mission safety.

8. AI INTEGRATION IN DISASTER-RESILIENT FANETS

Disaster-prone environments often damage communication infrastructure, and emergency teams must quickly establish alternative systems for sensing, coordination, and connectivity restoration. FANETs support rapid deployment, UAV mobility, and adaptable topology formation, which makes them suitable for disaster-response scenarios. FANET flexibility provides temporary communication service when terrestrial networks fail. Traditional FANET designs, however, still face major limitations under dynamic disaster conditions. Limited energy, link instability, scalability constraints, and strict real-time decision requirements reduce mission reliability [79].

AI integration into FANET architectures offers a practical response to these constraints and supports the development of more autonomous and resilient disaster-response networks. AI methods allow FANET nodes to learn from observed conditions, predict near-term outcomes, and adapt network behaviour according to operational feedback. Machine learning and deep learning methods support dynamic routing, path planning, node clustering, and energy optimisation through models that connect environmental and network states with suitable decisions. Reinforcement learning further improves real-time UAV movement and role assignment, which strengthens coverage continuity and connectivity stability while reducing collision risk and communication delay under mobility [9], [80]. Disaster operations benefit from AI-based capabilities because disaster scenes change rapidly and often require repeated reconfiguration of network roles and routes.

AI also supports intelligent task allocation and coordination across UAV swarms, which allows prioritization of mission-critical tasks such as victim detection, damage mapping, and emergency supply delivery. Computer vision and sensor-data fusion can process aerial imagery and environmental signals to produce actionable outputs for ground responders and incident command systems [81]. Predictive maintenance and fault detection also benefit from AI-based diagnostics, which can support early failure detection and can preserve network continuity during extended missions. AI-enabled FANETs therefore represent a class of self-organizing aerial networks that can operate under disaster constraints with improved adaptivity, efficiency, and robustness. Table 6 provides a detailed summary of AI applications in FANET-based disaster scenarios.

Table 6. AI applications in FANET-based disaster scenarios

Title/Year/Reference	AI Technique	Description	Limitations
Deep Learning Empowered Service Selection in FANETs: A 5G-Enabled UAV-Cloud Architecture [80] (2025)	Deep Learning integrated with Game Theory (DL-GT)	The DL-GT model couples a game-theoretic dataset based on Nash Equilibrium outcomes with a deep neural network that predicts a suitable service provider for UAV-cloud service requests. Model training uses simulated UAV interaction data, where client drones (CDs) and provider drones (PDs) negotiate under constraints that include QoS targets, price, and energy cost. The trained network outputs a service-selection decision that aims to improve service provisioning within a 5G-enabled UAV-cloud setting.	Validation relies on simulated data, and field evidence remains absent. Reported energy gains remain limited, and the scope remains narrow because the method targets service selection rather than broader routing and coordination. Security evaluation and adversarial robustness analysis remain absent, and real-world channel effects and hardware limits remain untested.
Green Edge Intelligence for Smart Management of a FANET in Disaster-Recovery Scenarios [82] (2023)	Model-Based Reinforcement Learning (RL) using Markov Decision Process (MDP)	A centralized FANET Controller (FC) runs a model-based RL policy that optimizes UAV takeoff decisions in a disaster area. The method uses an MDP that represents edge-computing service demand dynamics and variable renewable energy availability from a wind generator. The policy aims to balance energy usage and service provisioning so satellite-link reliance decreases, along with associated cost and latency.	Simulation evidence dominates the evaluation, and real-world testing remains absent. Simplified UAV and network models reduce deployment fidelity, and the design does not address multi-agent coordination. Full observability assumptions and stable renewable supply assumptions may not hold during real disasters. Security considerations remain unaddressed.
OLSR+: A new routing method based on fuzzy logic in FANETs [83] (2022)	Fuzzy Logic-Based Routing (OLSR+)	OLSR+ extends the Optimized Link State Routing (OLSR) protocol through fuzzy-logic selection of multipoint relays (MPRs) and routing paths. Route choice uses metrics such as estimated link lifetime, residual energy, and neighborhood density, with the goal of improving route stability and energy efficiency under mobility.	Additional routing parameters increase control overhead relative to protocols such as G-OLSR, and higher overhead can increase processing cost and channel occupancy. Rapidly changing FANET conditions can amplify the impact of this added complexity. Fuzzy-rule design and parameter tuning can also affect generalizability across

			different mobility and density regimes.
Distributed Routing Optimization Algorithm for FANET Based on Multiagent Reinforcement Learning [84] (2024)	Decentralized Execution Multiagent Deep Deterministic Policy Gradient (DE-MADDPG)	The approach formulates routing optimization as a MARL problem in which each UAV acts as an agent and uses local observations to adapt its routing behavior. Each agent can adjust the selected routing protocol, including AODV or DSDV, and tune protocol parameters, including hello-packet intervals. The training stage follows a centralized scheme, whereas the execution stage follows a decentralized scheme that relies on local information during deployment.	Performance claims rely on simulation-based evaluation, and field-deployment evidence remains absent. Consequently, the transferability of the proposed approach to real radios, real mobility patterns, and hardware-constrained UAV platforms remains uncertain. The training process also requires a representative set of disaster scenarios because a mismatch between the training environment and the deployment environment can reduce practical performance. Security risks and adversarial signaling threats also remain unaddressed.
UAV-to-UAV Communication Scheme for Enabling Emergency Services During Network Failure [85] (2022)	Dijkstra's Shortest Path Algorithm (used with M/M/1 Queue Model)	UAVs form a device-to-device communication grid that forwards emergency messages across multiple hops. Each UAV node follows an M/M/1 queue model, and the expected response time defines the link cost between neighboring UAV nodes. Dijkstra's algorithm selects the multi-hop path that minimizes the total response time from a mobile user to an emergency responder.	Equal service-rate assumptions across UAV nodes ignore real heterogeneity in computational load, radio performance, and battery state. Energy constraints, mobility effects, channel variability, and interference effects also remain absent from the model, although each condition can alter path optimality during real emergency deployments.

AI-based FANET solutions show stronger adaptability to dynamic disaster conditions than traditional rule-based methods. Most existing studies, however, remain simulation-based, which creates a clear need for validation through real-world experiments or testbeds.

9. FUTURE RESEARCH DIRECTIONS

UAV platforms improve disaster management through rapid situational awareness and timely delivery of aid and supplies to affected areas. Although the operational value of UAV platforms is clear, the research on UAV swarm networks remains at an early stage, and several unresolved challenges still limit their operational effectiveness. Technical constraints, regulatory limitations, and field-operational restrictions reduce reliability and large-scale deployment, particularly in environments where infrastructure is unstable. Practical and dependable UAV-assisted disaster response therefore requires deployment-oriented designs that address real field constraints and receive validation under real-time conditions.

Digital twin-enabled FANETs represent an important research direction, although most studies are conceptual or simulation-based [86]. A digital twin functions as a real-time virtual replica of the UAV swarm, communication links, and operational environment. Continuous telemetry updates keep the virtual replica synchronised with the physical system. Integration with AI methods, particularly multi-agent reinforcement learning, further supports adaptive relay selection, routing reconfiguration, clustering decisions, and handover control under dynamic disaster conditions with partial observability [1].

Flood and wildfire responses often involve rapid topology changes and link degradation. Short-horizon connectivity forecasting enables proactive UAV repositioning and task reassignment before link failure affects mission continuity. A digital twin provides connectivity forecasting through predictive evaluation of near-term network performance. Predictive evaluation then supports communication adaptation that preserves coverage and reliability when terrestrial infrastructure remains unavailable or damaged. Several open challenges still require focused research, which include channel and mobility model accuracy, telemetry synchronization latency, computational overhead on resource-constrained platforms, and cyber-security vulnerabilities in the digital twin and its communication interfaces. Robust operation under real-time constraints relies on solutions that improve model fidelity, synchronization efficiency, secure control interfaces, and scalable computation. Digital twin-assisted FANETs therefore represent a potential enabler of intelligent and resilient UAV-based disaster-response systems [87], [88], [89].

10. CONCLUSION

UAV deployment in disaster response requires adaptive, intelligent, and energy-efficient communication frameworks that sustain service during mobility and infrastructure disruption. The present review identified several critical challenges for UAV-based FANETs, which include high mobility, limited energy, link instability, and complex integration across heterogeneous systems. The review also addressed the role of artificial intelligence, particularly multi-agent reinforcement learning, in real-time decision support, autonomous route selection, and network resilience. Digital twin integration represents a valuable direction for predictive model development and operational optimisation when the digital twin remains synchronised with field telemetry.

Progress in the field remains constrained by the gap between simulation-based development and real-world deployment as the later requires stronger experimental validation and more realistic evaluation settings. Future research should prioritise lightweight, secure, and scalable communication protocols tailored to disaster scenarios, with clear attention to field constraints and reproducibility. Technology advances, when supported by rigorous validation, may transform UAV swarms into dependable operational assets that enhance situational awareness, coordination, and mission effectiveness across emergency and post-disaster operations.

ACKNOWLEDGMENT

My sincere appreciation goes to the Malaysia International Scholarship (MIS) for supporting my PhD journey. I am also deeply grateful to Prof. Madya Dr. Rozeha Bt. A. Rashid and Dr. Mohd. Adib bin Sarijari for their valuable guidance, continuous support, and constructive advice throughout this Journey.

REFERENCES

[1] E. A. Muin, M. A. Sarijari, R. A. Rashid, W. Ejaz, and M. N. M. Nasir, "Optimal Communication Handover of SAR Drone Based on Digital Twin Strategy," *Conf. Proc. - IEEE Int. Conf. Adv. Telecommun. Netw. Technol. Empower. Telecommun. Technol. Sustain. Futur. ATNT 2024*, vol. 1, pp. 1–4, 2024, doi: 10.1109/ATNT61688.2024.10719092.

[2] J. Angjo, I. Shayea, M. Ergen, H. Mohamad, A. Alhammadi, and Y. I. Daradkeh, "Handover Management of Drones in Future Mobile Networks: 6G Networks," *IEEE Access*, vol. 9, pp. 12803–12823, 2021, doi: 10.1109/ACCESS.2021.3051097.

[3] M. Basharat, M. Naeem, and A. Anpalagan, "Priority-based resource allocation in wireless powered UAV-assisted networks," *IET Networks*, vol. 11, no. 5, pp. 156–168, 2022, doi: 10.1049/ntw2.12044.

[4] O. K. Sahingoz, "Networking models in flying Ad-hoc networks (FANETs): Concepts and challenges," *J. Intell. Robot. Syst. Theory Appl.*, vol. 74, no. 1–2, pp. 513–527, 2014, doi: 10.1007/s10846-013-9959-7.

[5] W. Zafar and B. M. Khan, "A reliable, delay bounded and less complex communication protocol for multicluster FANETs," *Digit. Commun. Networks*, vol. 3, no. 1, pp. 30–38, 2017, doi: 10.1016/j.dcan.2016.06.001.

[6] J. Carvajal-Rodríguez, W. Moposita, C. Tipantuña, L. F. Urquiza, and D. Vega-Sanchez, "FANET Networks: Analysis of Routing Protocols," *ETCM 2024 - 8th Ecuador Tech. Chapters Meet.*, 2024, doi: 10.1109/ETCM63562.2024.10746121.

[7] T. K. Bhatia, S. Gilhotra, S. S. Bhandari, and R. Suden, "Flying Ad-Hoc Networks (FANETs): A Review," *EAI Endorsed Trans. Energy Web*, vol. 11, pp. 1–7, 2024, doi: 10.4108/ew.5489.

[8] W. D. Paredes, H. Kaushal, I. Vakilinia, and Z. Prodanoff, "LoRa Technology in Flying Ad Hoc Networks: A Survey of Challenges and Open Issues," *Sensors*, vol. 23, no. 5, 2023, doi: 10.3390/s23052403.

[9] J. Lansky *et al.*, "Reinforcement Learning-Based Routing Protocols in Flying Ad Hoc Networks (FANET): A Review," *Mathematics*, vol. 10, no. 16, pp. 1–60, 2022, doi: 10.3390/math10163017.

[10] M. A. Siddiqi, C. Iwendi, K. Jaroslava, and N. Anumbe, "Analysis on security-related concerns of unmanned aerial vehicle: attacks, limitations, and recommendations," *Math. Biosci. Eng.*, vol. 19, no. 3, pp. 2641–2670, 2022, doi: 10.3934/MBE.2022121.

[11] M. S. Yousefpoor and H. Barati, "DSKMS: a dynamic smart key management system based on fuzzy logic in wireless sensor networks," *Wirel. Networks*, vol. 26, no. 4, pp. 2515–2535, 2020, doi: 10.1007/s11276-019-01980-1.

[12] D. Shumeye Lakew, U. Sa'Ad, N. N. Dao, W. Na, and S. Cho, "Routing in Flying Ad Hoc Networks: A Comprehensive Survey," *IEEE Commun. Surv. Tutorials*, vol. 22, no. 2, pp. 1071–1120, 2020, doi: 10.1109/COMST.2020.2982452.

[13] B. Li, Z. Fei, Y. Zhang, and M. Guizani, "Secure UAV communication networks over 5G," *IEEE Wirel. Commun.*, vol. 26, no. 5, pp. 114–120, 2019, doi: 10.1109/MWC.2019.1800458.

[14] Z. Qadir, F. Ullah, H. S. Munawar, and F. Al-Turjman, "Addressing disasters in smart cities through UAVs path planning and 5G communications: A systematic review," *Comput. Commun.*, vol. 168, no. January, pp. 114–135, 2021, doi: 10.1016/j.comcom.2021.01.003.

[15] M. Marchese, A. Moheddine, and F. Patrone, "IoT and UAV integration in 5G hybrid terrestrial-satellite networks," *Sensors (Switzerland)*, vol. 19, no. 17, 2019, doi: 10.3390/s19173704.

[16] G. M. Cappello *et al.*, "Optimizing FANET Lifetime for 5G Softwarized Network Provisioning," *IEEE Trans. Netw. Serv. Manag.*, vol. 19, no. 4, pp. 4629–4649, 2022, doi: 10.1109/TNSM.2022.3193883.

[17] F. Wei, G. Feng, S. Qin, Y. Peng, and Y. Liu, "Hierarchical Network Slicing for UAV-Assisted Wireless Networks With Deployment Optimization," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 12, pp. 3705–3718, Dec. 2024, doi: 10.1109/JSAC.2024.3459055.

[18] A. Nadeem, A. Mehmood, and M. S. Siddiqui, "A Review and Classification of Flying Ad-Hoc Network (FANET) Routing Strategies," *Artic. Int. J. Sci. Basic Appl. Res.*, vol. 8, no. 3, pp. 1–8, 2018, [Online]. Available: www.textroad.com

[19] S. Abbas, M. Abu Talib, I. Ahmed, and O. Belal, "Integration of UAVs and FANETs in Disaster Management: A Review on Applications, Challenges

and Future Directions," *Trans. Emerg. Telecommun. Technol.*, vol. 35, no. 12, Dec. 2024, doi: 10.1002/ett.70023.

[20] I. N. Azmi, Y. M. Yussoff, M. Kassim, and N. M. Tahir, "A Mini-Review of Flying Ad Hoc Networks Mobility Model for Disaster Areas," *Int. Trans. J. Eng.*, vol. 12, no. 10, pp. 1–12, 2021, doi: 10.14456/ITJEMAST.2021.191.

[21] S. Yogarayan, "Wireless Ad Hoc Network of MANET, VANET, FANET and SANET: A Review," *J. Telecommun. Electron. Comput. Eng.*, vol. 13, no. 4, pp. 13–18, 2021.

[22] A. N. Uwaechia and N. M. Mahyuddin, "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges," *IEEE Access*, vol. 8, pp. 62367–62414, 2020, doi: 10.1109/ACCESS.2020.2984204.

[23] M. Ali, A. Idress, and J. Ibrahim, "FANET : - Communication Architecture and Routing Protocols A Review," vol. 24, no. 5, 2024.

[24] M. S. M. Al-dabbagh, "Exploiting Conventional MANET R outing in UAV ' s Based Environment," pp. 12–17, 2024.

[25] A. M. Soomro *et al.*, "In MANET: An Improved Hybrid Routing Approach for Disaster Management," *Proc. - 2023 IEEE Int. Conf. Emerg. Trends Eng. Sci. Technol. ICES T 2023*, pp. 1–6, 2023, doi: 10.1109/ICEST56843.2023.10138831.

[26] I. A. Alameri and J. Komarkova, "A Multi-Parameter Comparative Study of MANET Routing Protocols," *Iber. Conf. Inf. Syst. Technol. Cist.*, vol. 2020-June, no. June, pp. 24–27, 2020, doi: 10.23919/CISTI49556.2020.9141119.

[27] Y. Ozen and G. Z. Ozen, "A new priority aware routing protocol for efficient emergency data transmissions in MANETs," *Ad Hoc Networks*, vol. 163, no. May, p. 103592, 2024, doi: 10.1016/j.adhoc.2024.103592.

[28] M. A. Khan, I. M. Qureshi, and F. Khanzada, "A hybrid communication scheme for efficient and low-cost deployment of future flying AD-HOC network (Fanet)," *Drones*, vol. 3, no. 1, pp. 1–20, 2019, doi: 10.3390/drones3010016.

[29] T. R. Beegum, M. Y. I. Idris, M. N. Bin Ayub, and H. A. Shehadeh, "Optimized Routing of UAVs Using Bio-Inspired Algorithm in FANET: A Systematic Review," *IEEE Access*, vol. 11, no. January, pp. 15588–15622, 2023, doi: 10.1109/ACCESS.2023.3244067.

[30] X. Sun, D. W. K. Ng, Z. Ding, Y. Xu, and Z. Zhong, "Physical layer security in UAV systems: Challenges and opportunities," *IEEE Wirel. Commun.*, vol. 26, no. 5, pp. 40–47, 2019, doi: 10.1109/MWC.001.1900028.

[31] R. Dhall and S. Dhongdi, *Review of Protocol Stack Development of Flying Ad-hoc Networks for Disaster Monitoring Applications*, vol. 30, no. 1. Springer Netherlands, 2023. doi: 10.1007/s11831-022-09791-y.

[32] C. M. Cheng, P. H. Hsiao, H. T. Kung, and D. Vlah, "Performance measurement of 802.11a wireless links from UAV to ground nodes with various antenna orientations," *Proc. - Int. Conf. Comput. Commun. Networks, ICCCN*, pp. 303–308, 2006, doi: 10.1109/ICCCN.2006.286291.

[33] A. T. Albu-Salih and H. A. Khudhair, "ASR-FANET: An adaptive SDN-based routing framework for FANET," *Int. J. Electr. Comput. Eng.*, vol. 11, no. 5, pp. 4403–4412, 2021, doi: 10.11591/ijece.v11i5.pp4403-4412.

[34] K. Lim, "Bluetooth Core Specification," *Next Gener. Bluetooth Wi-Fi*, pp. 151–201, 2024, doi: 10.1002/9781394306688.ch6.

[35] F. Noor, M. A. Khan, A. Al-Zahrani, I. Ullah, and K. A. Al-Dhlan, "A review on communications perspective of flying AD-HOC networks: Key enabling wireless technologies, applications, challenges and open research topics," *Drones*, vol. 4, no. 4, pp. 1–14, 2020, doi: 10.3390/drones4040065.

[36] B. Van den Bergh, A. Chiumento, and S. Pollin, "Ultra-Reliable IEEE 802.11 for UAV Video Streaming: From Network to Application," 2017, pp. 637–647. doi: 10.1007/978-981-10-1627-1_50.

[37] X. Lin *et al.*, "The Sky is Not the Limit: LTE for Unmanned Aerial Vehicles," *IEEE Commun. Mag.*, vol. 56, no. 4, pp. 204–210, 2018, doi: 10.1109/MCOM.2018.1700643.

[38] O. Bazan and M. Jaseemuddin, "A survey on MAC protocols for wireless adhoc networks with beamforming antennas," *IEEE Commun. Surv. Tutorials*, vol. 14, no. 2, pp. 216–239, 2012, doi: 10.1109/SURV.2011.041311.00099.

[39] A. Li, G. Wu, C. Dong, and L. Zhang, "Cu-MAC: A MAC protocol for centralized UAV networks with directional antennas," *IEICE Trans. Commun.*, no. 5, pp. 537–544, 2020, doi: 10.1587/transcom.2019EBP3089.

[40] H. Hsu, "An Energy-Efficient Protocol For Wireless Sensor Networks," pp. 2321–2325, 2005.

[41] S. Temel and I. Bekmezci, "LODMAC: Location oriented directional MAC protocol for FANETs," *Comput. Networks*, vol. 83, pp. 76–84, 2015, doi: 10.1016/j.comnet.2015.03.001.

[42] "UD-M AC : D elay Tolerant M ultiple A ccess Control Protocol for Unm anned A erial V ehicle Networks".

[43] T. Van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," *SenSys'03 Proc. First Int. Conf. Embed. Networked Sens. Syst.*, pp. 171–180, 2003, doi: 10.1145/958491.958512.

[44] G. Wu, C. Dong, A. Li, L. Zhang, and Q. Wu, "FM-MAC: A Multi-Channel MAC Protocol for FANETs with Directional Antenna," *Proc. - IEEE Glob. Commun. Conf. GLOBECOM*, pp. 1–7, 2018, doi: 10.1109/GLOCOM.2018.8648025.

[45] T. Zheng, S. Radhakrishnan, and V. Sarangan, "PMAC: An adaptive energy-efficient MAC protocol for Wireless Sensor Networks," *Proc. - 19th IEEE Int. Parallel Distrib. Process. Symp. IPDPS 2005*, vol. 2005, pp. 65–72, 2005, doi: 10.1109/IPDPS.2005.344.

[46] S. Say, H. Inata, and S. Shimamoto, "A hybrid collision coordination-based multiple access scheme for super dense aerial sensor networks," *IEEE Wirel. Commun. Netw. Conf. WCNC*, no. Wcnc, 2016, doi: 10.1109/WCNC.2016.7565148.

[47] W. Wang, C. Dong, S. Zhu, and H. Wang, "DFRA: Demodulation-free random access for UAV ad hoc networks," *IEEE Int. Conf. Commun.*, pp. 1–6, 2017, doi: 10.1109/ICC.2017.7997364.

[48] A. Jiang, Z. Mi, C. Dong, and H. Wang, "CF-MAC: A collision-free MAC protocol for UAVs Ad-Hoc networks," *IEEE Wirel. Commun. Netw. Conf. WCNC*, vol. 2016-Septe, no. Wcnc, 2016, doi: 10.1109/WCNC.2016.7564844.

[49] P. Venkitasubramaniam, S. Adireddy, and L. Tong, "Opportunistic ALOHA and cross layer design for sensor networks," *Proc. - IEEE Mil. Commun. Conf. MILCOM*, vol. 1, pp. 705–710, 2003, doi: 10.1109/milcom.2003.1290190.

[50] L. Wang, H. Li, and Y. Jiang, "Adaptive-opportunistic Aloha: A media access control protocol for unmanned aerial vehicle-wireless sensor network systems," *Int. J. Distrib. Sens. Networks*, vol. 12, no. 8, 2016, doi: 10.1177/1550147716662785.

[51] M. M. Azari, F. Rosas, and S. Pollin, "Cellular connectivity for UAVs: Network modeling, performance analysis, and design guidelines," *IEEE Trans. Wirel. Commun.*, vol. 18, no. 7, pp. 3366–3381, 2019, doi: 10.1109/TWC.2019.2910112.

[52] M. M. Azari, F. Rosas, and S. Pollin, "Reshaping Cellular Networks for the Sky: Major Factors and Feasibility," *IEEE Int. Conf. Commun.*, vol. 2018-May, 2018, doi: 10.1109/ICC.2018.8422685.

[53] M. Mozaffari, W. Saad, M. Bennis, Y. H. Nam, and M. Debbah, "A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems," *IEEE Commun. Surv. Tutorials*, vol. 21, no. 3, pp. 2334–2360, 2019, doi: 10.1109/COMST.2019.2902862.

[54] Asiva Noor Rachmayani, "Federal Aviation Administration (FAA), UAS Traffic Management Research Transition Team Plan, Federal Aviation Administration (FAA," p. 6, 2017.

[55] E. Kalantari, H. Yanikomeroglu, and A. Yongacoglu, "On the Number and 3D Placement of Drone Base Stations in Wireless Cellular Networks," 2016.

[56] J. Lyu, Y. Zeng, R. Zhang, and T. J. Lim, "Placement Optimization of UAV-Mounted Mobile Base Stations," *IEEE Commun. Lett.*, vol. 21, no. 3, pp. 604–607, 2017, doi: 10.1109/LCOMM.2016.2633248.

[57] F. M. Kalarde and M. Sabbaghian, "Efficient 3D Placement of an Aerial Base Station in Cellular Communication," *IWCIT 2021 - 2021 9th Iran Work. Commun. Inf. Theory*, 2021, doi: 10.1109/IWCIT53998.2021.9519619.

[58] S. Rohde, M. Putzke, and C. Wietfeld, "Ad hoc self-healing of OFDMA networks using UAV-based relays," *Ad Hoc Networks*, vol. 11, no. 7, pp. 1893–1906, 2013, doi: 10.1016/j.adhoc.2012.06.014.

[59] M. Alzenad, A. El-Keyi, and H. Yanikomeroglu, "3-D Placement of an Unmanned Aerial Vehicle Base Station for Maximum Coverage of Users with Different QoS Requirements," *IEEE Wirel. Commun. Lett.*, vol. 7, no. 1, pp. 38–41, 2018, doi: 10.1109/LWC.2017.2752161.

[60] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Wireless communication using unmanned aerial vehicles (UAVs): Optimal transport theory for hover time optimization," *IEEE Trans. Wirel. Commun.*, vol. 16, no. 12, pp. 8052–8066, 2017, doi: 10.1109/TWC.2017.2756644.

[61] E. Koyuncu, "Power-Efficient Deployment of UAVs as Relays," *IEEE Work. Signal Process. Adv. Wirel. Commun. SPAWC*, vol. 2018-June, pp. 1–15, 2018, doi: 10.1109/SPAWC.2018.8445865.

[62] M. Chen, M. Mozaffari, W. Saad, C. Yin, M. Debbah, and C. S. Hong, "Caching in the Sky: Proactive Deployment of Cache-Enabled Unmanned Aerial Vehicles for Optimized Quality-of-Experience," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 5, pp. 1046–1061, 2017, doi: 10.1109/JSAC.2017.2680898.

[63] H. Wang, G. Ding, F. Gao, J. Chen, J. Wang, and L. Wang, "Power Control in UAV-Supported Ultra Dense Networks: Communications, Caching, and Energy Transfer," *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 28–34, 2018, doi: 10.1109/MCOM.2018.1700431.

[64] M. M. Azari, Y. Murillo, O. Amin, F. Rosas, M. S. Alouini, and S. Pollin, "Coverage maximization for a poisson field of drone cells," *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, vol. 2017-Octob, pp. 1–6, 2017, doi: 10.1109/PIMRC.2017.8292753.

[65] I. Bekmezci, E. Senturk, and T. Turker, "Security Issues in Flying Ad-Hoc Networks (FANETs)," *J. Aeronaut. Sp. Technol.*, vol. 9, no. October, pp. 13–21, 2015.

[66] A. Cretu, D. Radu, K. Nandor, C. Avram, C. Domuta, and A. Astilean, "Neural Networks Fire Detection in a Public Safety Fog System," *2020 22nd IEEE Int. Conf. Autom. Qual. Testing, Robot. - THETA, AQTR 2020 - Proc.*, pp. 22–27, 2020, doi: 10.1109/AQTR49680.2020.9129925.

[67] D. Simoes, A. Rodrigues, A. B. Reis, and S. Sargento, "Forest Fire Monitoring through a Network of Aerial Drones and Sensors," *2020 IEEE Int. Conf. Pervasive Comput. Commun. Work. PerCom Work. 2020*, 2020, doi: 10.1109/PerComWorkshops48775.2020.9156137.

[68] S. Bharany *et al.*, "Wildfire Monitoring Based on Energy Efficient Clustering Approach for FANETS," *Drones*, vol. 6, no. 8, pp. 1–19, 2022, doi: 10.3390/drones6080193.

[69] H. S. Munawar, F. Ullah, S. Qayyum, S. I. Khan, and M. Mojtahedi, "Uavs in disaster management: Application of integrated aerial imagery and convolutional neural network for flood detection," *Sustain.*, vol. 13, no. 14, 2021, doi: 10.3390/su13147547.

[70] A. F. M. S. Shah, "Architecture of Emergency Communication Systems in Disasters through UAVs in 5G and Beyond," *Drones*, vol. 7, no. 1, 2023, doi: 10.3390/drones7010025.

[71] Y. Liu, J. Xie, C. Xing, S. Xie, and B. Ni, "Construction of FANETs for user coverage and information transmission in disaster rescue scenarios," *Comput. Commun.*, vol. 207, pp. 164–174, Jul. 2023, doi: 10.1016/j.comcom.2023.05.014.

[72] C. Qu, R. Singh, A. E. Morel, F. B. Sorbelli, P. Calyam, and S. K. Das, "Obstacle-Aware and Energy-Efficient Multi-Drone Coordination and

Networking for Disaster Response," *Proc. 2021 17th Int. Conf. Netw. Serv. Manag. Smart Manag. Futur. Networks Serv. CNSM 2021*, pp. 446–454, 2021, doi: 10.23919/CNSM52442.2021.9615574.

[73] A. Ghosh, B. B. Dash, S. S. Patra, T. N. Pandey, B. K. Pattanayak, and U. C. De, "Performance Evaluation of Drones in FANETs using Queueing Model," *Int. Conf. Sustain. Commun. Networks Appl. ICSCNA 2023 - Proc.*, no. Icscna, pp. 43–48, 2023, doi: 10.1109/ICSCNA58489.2023.10370671.

[74] S. A. Hasan, M. A. Mohammed, and S. K. Sulaiman, "Flying Ad-Hoc Networks (FANETs): Review of Communications, Challenges, Applications, Future direction and Open Research Topics," *ITM Web Conf.*, vol. 64, p. 01002, 2024, doi: 10.1051/itmconf/20246401002.

[75] I. Chandran and K. Vipin, "Multi-UAV Networks for Disaster Monitoring: Challenges and Opportunities from a Network Perspective," *SN Comput. Sci.*, vol. 5, no. 5, 2024, doi: 10.1007/s42979-024-02788-3.

[76] M. Micheletto *et al.*, "Flying real-time network to coordinate disaster relief activities in urban areas," *Sensors (Switzerland)*, vol. 18, no. 5, pp. 1–20, 2018, doi: 10.3390/s18051662.

[77] S. Yadav, M. C. Trivedi, V. K. Singh, and M. L. Kolhe, "Securing AODV routing protocol against black hole attack in MANET using outlier detection scheme," *2017 4th IEEE Uttar Pradesh Sect. Int. Conf. Electr. Comput. Electron. UPCON 2017*, vol. 2018-Janua, pp. 1–4, 2017, doi: 10.1109/UPCON.2017.8251012.

[78] P. A. Patil, R. S. Deshpande, and P. B. Mane, "Trust and Opportunity Based Routing Framework in Wireless Sensor Network Using Hybrid Optimization Algorithm," *Wirel. Pers. Commun.*, vol. 115, no. 1, pp. 415–437, 2020, doi: 10.1007/s11277-020-07579-6.

[79] S. K. Singh, "A Comprehensive Survey on Fanet : Challenges and Advancements," vol. 6, no. 3, pp. 2010–2013, 2015.

[80] M. B. E. N. Bezziane *et al.*, "Deep Learning Empowered Service Selection in FANETs : A 5G-Enabled UAV-Cloud Architecture," no. April, pp. 63877–63894, 2025.

[81] N. Cheng *et al.*, "AI for UAV-Assisted IoT Applications : A Comprehensive Review," *IEEE Internet Things J.*, vol. 10, no. 16, pp. 14438–14461, 2023, doi: 10.1109/JIOT.2023.3268316.

[82] G. Faraci, S. A. Rizzo, and G. Schembra, "Green Edge Intelligence for Smart Management of a FANET in Disaster-Recovery Scenarios," *IEEE Trans. Veh. Technol.*, vol. 72, no. 3, pp. 3819–3831, 2023, doi: 10.1109/TVT.2022.3217331.

[83] A. M. Rahmani *et al.*, "OLSR+: A new routing method based on fuzzy logic in flying ad-hoc networks (FANETs)," *Veh. Commun.*, vol. 36, p. 100489, 2022, doi: 10.1016/j.vehcom.2022.100489.

[84] Y. Ke *et al.*, "Distributed Routing Optimization Algorithm for FANET Based on Multiagent Reinforcement Learning," *IEEE Sens. J.*, vol. 24, no. 15, pp. 24851–24864, 2024, doi: 10.1109/JSEN.2024.3415127.

[85] A. Alnoman, "UAV-to-UAV Communication Scheme for Enabling Emergency Services During Network Failure," *2022 Int. Conf. Electr. Comput. Technol. Appl. ICECTA 2022*, pp. 291–294, 2022, doi: 10.1109/ICECTA57148.2022.9990222.

[86] B. M. Mohammad El-Basioni, "Data-driven joint routing, topology, and mobility design for FANET systems using a digital twin approach," *J. Electr. Syst. Inf. Technol.*, vol. 12, no. 1, pp. 1–31, 2025, doi: 10.1186/s43067-024-00185-7.

[87] R. Raza and F. Aadil, "A comprehensive survey on FANET-IoT-IoV interactions: challenges, opportunities, and future directions in 6G-enabled smart cities," *Computing*, vol. 108, no. 1, p. 10, Jan. 2026, doi: 10.1007/s00607-025-01602-z.

[88] E. Mustafa, J. Shuja, F. Rehman, M. Bilal, and M. S. Riaz, "UAVs and Federated Learning-Enabled Digital Twins of Vehicles in Dynamic Disaster Environments," 2025, pp. 415–427. doi: 10.1007/978-3-031-98349-8_22.

[89] J. R. McColl-Kennedy *et al.*, *Digital twins: a game changer in customer experience*, no. January. 2025. doi: 10.1108/JOSM-12-2024-0540.