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Flying ad hoc network applications, mobility models, routing protocols, and challenges: a review

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ABSTRACT

Applications of unmanned aerial vehicles (UAVs) are rapidly increasing in surveillance, disaster management, precision agriculture, logistics, environmental monitoring, and intelligent transportation systems. UAVs/drones have made their way towards the application of ad hoc networks. Multiple interconnected UAVs flying together have presented us with a new type of ad hoc network known as flying ad hoc networks (FANETs). While multiple small UAVs acting as a FANET offer a lot of benefits, there are also several challenges concerning this type of network. This study presents a systematic literature review (SLR) of FANET technologies by reviewing recent literature published between 2017 and 2025 from IEEE Xplore, Scopus, ScienceDirect, and Google Scholar databases. A structured review methodology based on inclusion and exclusion criteria was adopted to analyze more than 150 research articles. The study presents a comprehensive taxonomy of FANET mobility models and routing protocols, along with a comparative analysis of communication architectures, trajectory optimization methods, and implementation challenges. The findings reveal that routing efficiency, adaptive mobility models, secure communication, energy optimization, and scalable architectures are the major determinants of FANET performance. This article concludes that good connectivity, improved security, effective routing, carefully selected mobility models, and the architecture of FANET nodes are key parameters for obtaining optimal results.

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1. INTRODUCTION

Flying ad hoc networks (FANETs) have emerged as a critical advancement in wireless communication, enabling unmanned aerial vehicles (UAVs) to function as autonomous nodes within dynamic and highly mobile network structures. Despite their numerous applications in surveillance, search and rescue, military reconnaissance, and disaster recovery, FANETs face significant challenges. These challenges include high mobility, frequent topology changes, low node density, energy limitations, and complex routing mechanisms. The current research lacks a comprehensive framework that optimally addresses these issues while ensuring seamless communication, efficient routing, and fault tolerance in

FANETs. Therefore, there is a need to develop an efficient, adaptive, and scalable model in diverse operational environments.

In recent times, the application of UAVs/drones is ranging from research to commercial domains, including real-time surveillance, reconnaissance missions, goods delivery, and environment monitoring [1]–[5]. Networks play a vital role in technological advancements. With evolving technologies, networks are also rapidly and dynamically evolving. UAVs/drones have also made their way to the distribution of networks opening up a new domain of networks called FANETs. FANETs can be categorized as a subclass of mobile ad hoc networks (MANETs) where multiple micro air vehicles/drones are used to provide a communication network. These UAVs organize themselves autonomously and wirelessly communicate with each other, and a link is established with a ground station [6]. The autonomy of the UAVs working in a FANET depends upon the application and network type, whether the nodes are controlled and operated by a ground station or autonomously controlled by the UAVs themselves. The complex and rapidly changing requirements of communication networks require a more subtle, mobile and comprehensive architecture, that is the reason FANETs outscore conventional satellite communication systems as the conventional satellite technology requires massive fixed ground and space infrastructure, also the higher communication latency in different application scenarios can seriously affect the overall performance of the respective application.

It has been several years since single drone/UAV systems were applied across different domains to accomplish missions. These systems employ a single large UAV that is connected with a control station having a ground infrastructure. This connectivity with the ground infrastructure requires complex hardware onboard the UAV [7]. Single UAV systems are complex and vulnerable; failure of the UAV can cause serious implications for the whole mission and can even cause a complete failure [8]. Owing to this fragility and vulnerability, and advancements in embedded systems and wireless communications, multiple small drones/UAV can be organized to work simultaneously at comparatively lower costs than a single UAV system. The multi drone/UAV systems can overcome the basic problems of single UAV systems and can offer reliability and redundancy. When multiple nodes are interoperated failure of a single node will not affect the complete system, whereas the failure of a proportion of the nodes might impact the performance of the system, but it will not jeopardize the whole mission [8]–[10]. The performance and ability of the multi drone/UAV systems can be enhanced and improved by adding more nodes to the system.

The communication architecture is further divided into two subcategories in multi drone/UAV system [11]. The localization data needs to be updated frequently due to the dynamic and highly mobile movement of nodes in almost all types of FANETs [12]. Table 1 compares three types of wireless ad hoc networks: MANETs, vehicular ad hoc networks (VANETs), and FANETs. Although all three networks support ad hoc communication without fixed infrastructure, they differ significantly in their mobility, communication characteristics, and network requirements. MANETs consist of mobile devices such as smartphones and laptops, which typically exhibit low mobility and high node density. VANETs are formed by vehicles communicating with each other and roadside infrastructure. They have medium mobility, as vehicle movement is constrained by road networks and can often be predicted. FANETs consist of UAVs or drones that exhibit high mobility and rapid topology changes. MANETs, VANETs, and FANETs differ in mobility, energy constraints, and communication models [13]–[15]. FANETs exhibit high mobility, line-of-sight (LOS) communication, and low node density. There are several different challenges for FANETs due to their specialized characteristics and features such as high mobility, interconnectivity between nodes, dynamic topology changes, low node density, and frequent network changes. A systematic literature review (SLR) and taxonomy for the challenges related to FANETs have been devised in the latter part of this article.

Although many studies have explored different aspects of FANETs, some key research gaps remain. There is a lack of systematic comparisons to evaluate the performance of different routing and mobility models under various conditions. Existing models do not effectively use dynamic optimization strategies to enhance efficiency and fault tolerance. Research has mainly focused on connectivity and routing but has not sufficiently addressed energy constraints affecting UAV performance and network durability. Security challenges, such as protection against cyber threats like jamming and unauthorized access, have received minimal attention. Additionally, most studies rely on simulations, with limited real-world deployment to test proposed models under practical conditions.

In order to understand the challenges pertaining to FANETs, it’s pertinent to understand different applications of the FANET, as each application can have different implications and impacts on the performance of the FANET. Search queries used to retrieve literature from Google Scholar include FANET applications, routing in FANET, FANET mobility models, and challenges in FANET. These terms were carefully selected to cover a broad range of topics related to FANETs, focusing on their applications, routing strategies, mobility behavior, and the major challenges encountered in their deployment and performance.

Table 1. MANET, VANET, and FANET comparison

Class		MANET	VANET	FANET
Link type	Ad hoc	✓	✓	✓
	Direct link	✓	✓	✓
	Satellite	×	×	✓
	Cellular	×	✓	✓
Characteristics	Degree of mobility	Low	Medium	High
	Mobility models	Random way-point (RWP)	Prediction based	SRCM, realistic
	Energy limitations	High	Low	Medium
	Radio propagation model	NLOS	NLOS	LOS
	Localization method	GPS	Assisted-GPS, differential GPS	IMU
	Node density	High	Medium	Low

Only relevant results were included in the review, excluding results that did not contain keywords and were older than 2017. Literature from Elsevier and IEEE was preferred to be included into the review. A comprehensive table has been formulated with the top 10 results from each search query. The selected literature has been reviewed on the basis of covered areas of the FANET, including mobility modes, applications, trajectory optimization, communication architecture, routing protocols, and challenges.

Some of the common applications available in the literature are discussed in section 3. Section 4 discusses the mobility models of the FANET and trajectory optimization. Section 5 discusses routing in the FANET with a taxonomy of routing protocols. In section 6, challenges are reviewed for the FANET. Finally, section 7 contains conclusions of the article. This review contributes toward applied sciences and intelligent communication systems by providing researchers, engineers, and policymakers with a comprehensive understanding of FANET architectures, operational limitations, and emerging research directions.

2. RELATED WORK

Several FANET-related topics have been explored and investigated over the last several years, including computing environments. Following this trend, several studies have been conducted to provide reviews and solve various FANET difficulties. Nazib and Moh [16] explored the routing protocols for UAV networks, which included topology-based, position-based, hierarchical, deterministic, stochastic, and social-network-based protocols. Following that, the routing protocols were qualitatively compared in terms of their primary features, characteristics, and performance. Silva *et al.* [17] introduced STFANET, a software-defined networking (SDN)-based topology management system for FANETs. Bujari *et al.* [18] analyzed various existing mobility models and their deployment for various FANET applications. Chriki *et al.* [19] discussed FANETs from the standpoint of communication and technical issues by evaluating FANET routing protocols, mobility, and trajectory optimization models. Khan *et al.* [20] investigated several communication architectures, including existing wireless technologies, to achieve smooth wireless connectivity. In terms of design, it was determined that multi-layer UAV ad hoc networks are the best choice. Noor *et al.* [21] studied the primary enabling communication technologies in terms of data speed, spectrum type, coverage, and latency. Application possibilities, as well as the viability of key enabling technologies, were investigated. Oubbati *et al.* [22] investigated the movement information and the residual energy level of communication stability in order to anticipate the occurrence of a sudden connection failure. Sadiq and Salawudeen [23] presented an endpoint path traffic model to enhance the FANET communication connection. Lakew *et al.* [24] provided UAV classification, communications and utility designs, as well as a review of current FANET routing protocols.

Several studies on FANETs have been undertaken in the last year. Throughout the comprehend and determine the latest trends in our field of research, this study analyzed 10 academic papers using the search keywords “survey” and “flying ad hoc networks” in the last year. Lee *et al.* [25] propose an energy-aware, predictive fuzzy logic-based routing scheme for FANETs (drone networks). It uses node scoring (movement direction, energy, link quality, and stability) to prevent broadcast storms, and a fuzzy system to select optimal routes. Arafat and Moh [26] suggested a unique Q-learning-based topology-aware routing (QTAR) protocol for FANETs based on Q-learning. The designed routing protocol sought to deliver reliable connections between the source and destination by enhancing routing decisions by taking two-hop neighbor nodes into account and expanding the local perspective of the network topology. Khan *et al.* [27] offered a revolutionary routing approach called the flying nature-inspired algorithm, which is essentially an ant-based ad hoc network (AntHocNet) extension. The authors also conducted a case study to boost signal power using a decision tree learning technique. Blockchain technology has the potential to effectively address IoT security problems.

Abdelhafidh *et al.* [28] conducted research in which they classified assaults against IoT, VANETs, and FANETs systems based on their vulnerabilities and also investigated a variety of blockchain-based solutions for IoT, VANETs, and FANETs security advancements. Zeng and Zhang [29] examined the use of reinforcement learning in several FANET contexts such as routing protocols, flight trajectory selection, relaying, and charging applications. Mansour *et al.* [30] proposed a cross-layer and energy-aware (CLEA)-ad hoc on-demand distance vector (AODV) routing protocol for improving the performance and energy efficiency of FANETs. Srinivas *et al.* [31] proposed “trellis trimming” approach for assessing the likelihood of different range hypotheses and eliminating pathways with the lowest likelihood using Bayesian filters. The suggested strategy lowers the likelihood of selecting range ambiguity improperly. Srinivas *et al.* [32] investigated strategies for localizing multi-antenna users by using range estimations. Srinivas *et al.* [32] also addressed multi-antenna platform joint position and orientation tracking methods.

Agrawal and Kapoor [33] conducted a survey that included a comparison of numerous regional routing systems. The developers of the survey examined all of the global routing protocols in a typical network scenario with a variable number of nodes. Agrawal and Kapoor [33] conducted a thorough examination of geographic-based routing protocols, classifying them based on route and packet forwarding techniques. This literature also provided an extendable architecture for area distribution, with the objective of boosting coverage while minimizing the number of UAVs necessary without sacrificing operational performance [33]. Although there has been a lot of research and literature reviews on FANETs, our review paper offers a comprehensive base of existing FANET applications, mobility models, routing protocols, and challenges, and suggests development of a dynamic model for identification of the most appropriate parameters of FANET to achieve maximum efficiency and fault tolerance, as shown in Table 2.

Table 2. Literature review companions

Reference	Focus area	Key contributions	Limitations
Arafat and Moh [26], Nazib and Moh [16]	Routing Protocols	Explored various routing protocols for UAV networks and compared them qualitatively.	Lacks quantitative performance evaluation.
Silva *et al.* [17]	Topology management	Introduced STFANET, an SDN-based topology management system for FANETs.	No real-world deployment validation.
Bujari *et al.* [18]	Mobility models	Analyzed mobility models and their application to FANETs.	Limited discussion on real-world implementation challenges.
Chriki *et al.* [19]	Communication and routing	Evaluated FANET routing, mobility, and trajectory optimization models.	Did not provide simulation results.
Khan *et al.* [20]	Communication architectures	Investigated wireless technologies for FANET connectivity.	Lacks a detailed comparison of different architectures.
Noor *et al.* [21]	Enabling technologies	Studied communication technologies based on speed, spectrum, coverage, and latency.	Limited experimental validation.
Oubbati *et al.* [22]	Stability prediction	Analyzed movement and energy level to predict connection failures.	No real-world implementation or testing.
Sadiq and Salawudeen [23]	Path traffic model	Proposed an endpoint path traffic model to enhance communication.	Did not consider real-time dynamic topology changes.
Lakew *et al.* [24]	UAV Classification and routing	Reviewed FANET routing protocols and UAV communication designs.	Limited practical application insights.
Lee *et al.* [25]	Routing protocol design	Outperforming existing methods in delay, delivery rate, and stability	The scheme requires extra score-sharing and route-recovery messaging
Arafat and Moh [26]	Artificial intelligence (AI)-based routing	Suggested QTAR, a Q-learning-based routing protocol.	Needs validation in high-mobility scenarios.
Khan *et al.* [27]	AI-based routing	Proposed an AntHocNet extension and decision tree-based signal power optimization.	No comparison with traditional routing protocols.
Abdelhafidh *et al.* [28]	Security	Classified IoT, VANET, and FANET attacks and reviewed blockchain-based security.	Lacks real-time security implementation.
Zeng and Zhang [29]	Reinforcement learning	Explored RL applications in FANETs for routing, trajectory, and charging.	No detailed energy consumption analysis.
Mansour *et al.* [30]	CLEA-AODV	CLEA-AODV improves FANET routing by combining GSO-based energy-aware cluster head selection with a cooperative cross-layer MAC.	It's validated only through NS-2 simulation, not real-world UAV deployment.
Srinivas *et al.* [31]	Range estimation	Proposed “trellis trimming” for better range hypothesis selection.	Needs comparison with other range estimation methods.
Srinivas *et al.* [32]	Multi-antenna localization	Investigated localization techniques for multi-antenna users.	Limited discussion on error mitigation.
Agrawal and Kapoor [33]	Routing protocol comparison	Conducted a survey on regional/global routing protocols and proposed an extendable architecture.	Did not test the proposed architecture in real-world scenarios.

3. FANET APPLICATIONS

Applications of FANETs range from surveillance to environmental monitoring and relaying networks. Following is some of the different FANET application categories.

3.1. Search and rescue application

Search and rescue is trusted to be one of the most popular applications of FANETs, where the FANET nodes are used as flying cameras to capture real-time audio and video feeds in order to locate a ground target in search and rescue missions [34]. The autonomous flight of the UAVs allows them to access complex terrains, which is difficult and risky for humans; the information collected from these UAVs is used to target the rescue missions [35]. UAVs have been used in Hurricane Katrina, Fukushima, and Nepal earthquakes in 2005, 2011, and 2015, respectively, for search and rescue missions [36].

3.2. Traffic monitoring application

The FANET nodes can also be used as observational infrastructure in traffic and urban monitoring scenarios [37]. In case of disaster, the roadside fixed traffic management and monitoring system including the computing, communications and electric systems can be compromised whereas FANET can be used alternatively to collect and rely back the information and data in form of video streaming and images to control center to effectively manage the situations.

3.3. Reconnaissance application

UAVs have been conventionally used for aerial surveillance and reconnaissance missions for quite a long time. The introduction of FANET nodes being used in hostile territories as aerial reconnaissance infrastructure to collect information and help the military on the ground has revolutionized the whole reconnaissance process. The use of FANET ranges from military operations to law enforcement activities [38].

3.4. Smart agriculture and farming application

The FANET nodes are also used for agricultural management and monitoring of crops. The nodes sense crop health and environmental variables for effective agricultural management [39], [40]. Lugo *et al.* [41] developed an architecture for FANETs to enable monitoring of water quality in a shrimp farm that directly influences shrimp survival and healthy growth.

3.5. Environment monitoring application

The FANET nodes are also used as remote/environmental sensing infrastructure, where the nodes collect environmental information from a specific area and relays to a ground station. Nodes are arranged in proximity as a sensor network and typically monitor environmental variables like humidity, temperature, air pressure, intensity of light, and pollution levels [42], [43]. Making the effective environment management concept of smart cities possible.

3.6. Communication networks application

The FANET nodes can also be deployed in a complex fashion in order to relay communications networks in areas with a special need for connectivity. Including but not limited to the areas affected by a disaster where ground communications networks have been affected. Flying nodes are used as airborne communication relays to effectively connect with a ground control station for exchange of information [19].

3.7. Border surveillance application

The FANET nodes can also be applied for international border surveillance in order to facilitate legitimate goods movement, thwart crimes, maintain border safety, and secure the natural resources in border areas. Typically, the FANET can be used in surveillance and remote sensing arrangements for this type of application [44]. A critical aspect is, surely, the effective management and coordination of these new UAV devices in order to formulate specific strategies necessary to facilitate the agriculture humans' operators [45]. These are only a few applications of the FANET, but it is not limited to only a few; it goes far beyond, ranging from military to research and from commercial to educational applications. With a dynamic and diverse range of applications, FANETs come with several challenges and issues; these challenges are discussed in the later part of this article.

This study primarily relies on literature reviews and simulations, lacking real-world experimental validation. It focuses on theoretical frameworks without proposing a concrete FANET communication model. While security aspects are mentioned, they are not deeply analyzed or tested for practical use. The literature review covers studies from 2017 onward, potentially missing important earlier research. Additionally, the study does not extensively address sector-specific performance metrics, even though FANET applications vary across industries. Despite these limitations, the research helps expand knowledge by highlighting key challenges and future opportunities in network optimization, energy management, and security improvements.

4. FANET MOBILITY MODELS AND TRAJECTORY OPTIMIZATION

Figure 1 provides a taxonomy of FANET mobility models. These are categorized into six main types based on their characteristics and behavior patterns. The following is a brief explanation of each.

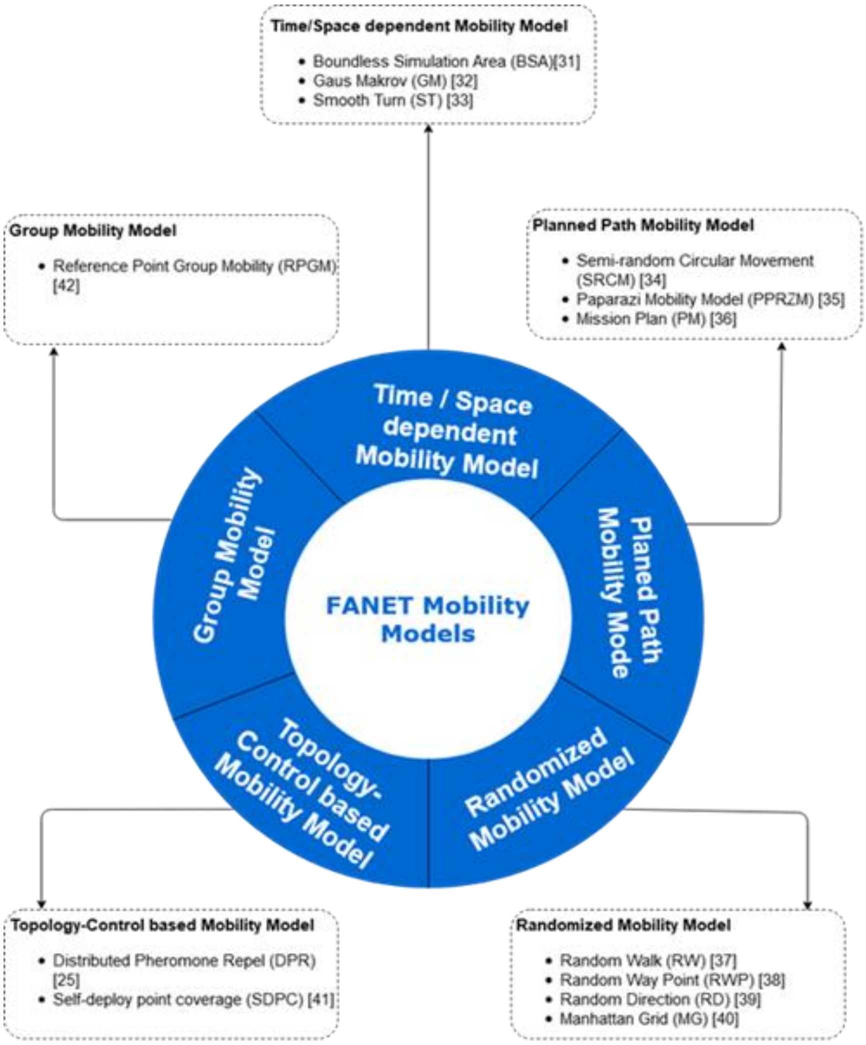

Figure 1. FANET mobility models taxonomy

4.1. Mobility models

For the simulation of real-time movement of nodes within a FANET, mobility models are used. These models present variation over time for the node position, acceleration, and velocity. With the complex and diverse application range of the FANET, mobility and movement models of the FANET nodes are very dynamic. From the literature, this study can identify five classes of mobility models in FANET.

4.2. Time/space dependent mobility model

In this mobility model, the nodes are bound to avoid sharp speed and direction changes. Different mathematical models can be applied to achieve plane and uniform movement of nodes. Boundless simulation area (BSA) [46] and Gauss-Markov (GM) [47] use previous and current speed and direction variables to accumulate new values at every iteration. Another example of this type of mobility model is the smooth turn (ST) [48] mobility model, where mobile nodes circle in curved trajectories around a selected point in space and keeps its course until the node is provided with another point in space.

4.3. Planned path mobility model

In this model, the nodes are provided with a predefined vector shape to follow along. The nodes follow the path until it ends, and after reaching the end point, it could randomly switch to another pattern or can simply loop with the given path until commanded to change. Semi-random circular movement (SRCM) [49] is engineered for curved mobility maneuvers, suitable for node movement around a specific point. Another example of this model is the paparazzi mobility model (PPRZM) [50], which contains several predefined movement patterns like eight, oval, stay-at, waypoints, and scan. Each node in the FANET adapts to one of the predefined paths at a random speed. In the mission plan (MP) [51] mobility model, the flight trajectory is predefined, and nodes are equipped with the flight plans.

4.4. Randomized mobility model

In this model, the movement of each node is independent of the others. These are simple mobility models and are normally used for network research. Each node in this model randomly adopts a way-point and acceleration for a specific time period. random walk (RW) [52], RWP [53], random direction (RD) [54], and Manhattan grid (MG) [55] are some examples of this mobility model. In MG, the nodes are bound to move horizontally and vertically in a grid topology. Lin *et al.* [56] proposed a three-dimensional (3D) smooth RW mobility model that has the capability to mimic the movement of the UAV in 3D space.

4.5. Topology-control based mobility model

In this model, real-time control of mobile node topology is retained in order to satisfy dynamic movement requirements in certain scenarios. Distributed pheromone repel (DPR) [35] and self-deploy point coverage (SDPC) [57] are examples of this mobility model. With DPR, every node within the FANET maintains its own pheromone map. With SDPC, a set of nodes is deployed in a disaster-struck area to provide a communications network infrastructure that can be used by victims and rescue operation teams. This mobility model targets to equip the nodes to cover the maximum area and number of people on the ground and maintain constant connectivity with other nodes in the infrastructure.

4.6. Group mobility model

The nodes in this mobility model are forced to travel in groups, with spatial constraints between them. This mobility concept is shown by reference point group mobility (RPGM) [58]. The nodes in this model represent a random movement around a fixed point. Each node is restricted to moving around a reference point on a specified line. Li *et al.* [59] suggested a particle swarming UAV node-based particle swarm mobility model (PSMM). PSMM's most admirable feature is its ability to simulate UAV swarm movement using a basic computational framework. Li *et al.* [60] provided a non-trivial mobility model for mission planning in the first stage by proposing a set of ideas and metrics for observed area coverage of the UAV swarm.

4.7. Trajectory optimization

The FANET has a unique and unmatched feature allowing nodes to dynamically and quickly adjust their position by relocating. However, environmental changes can impact the nodes and can cause node failure, location changes, and ground terminal density. The relocation feature of the nodes in a FANET equips them with extensive performance gains, including but not limited to enhanced coverage and ground terminal density. Let’s take an example of a search and rescue mission, which is time-critical: a trajectory is required where the nodes can consistently communicate with the ground control station; an effective trajectory is vital for mission success. Communication with the ground control stations for most commercial UAVs is point-to-point, typically on unlicensed radio spectrum. Calculation of optimal node trajectory is a complex task in the FANET, even in simpler and static missions, and the degree of complexity increases with the increase in the number of nodes in the FANET [61]. Trajectory/path of the FANET nodes plays a key role in the optimization of the network performance and practicality of the application. Over the past few years, a lot of research work has been done for the optimization of trajectory in FANETs; typically, two types of node deployment exist: static and dynamic.

4.7.1. Static node deployment

Optimal placement of the FANET nodes in order to increase the coverage area and the introduction of several algorithms is done by [62]–[65]. In this literature, it is assumed that the nodes can cover a ground terminal density if they are within a specific range and the distance between them is not more than a specific limit. The average throughput of the nodes has been studied as an objective function with the addition of a possible hover time constraint by [66]. In studies [67]–[69] explored static placement of nodes as relays for cellular traffic, generic multichip communication, and random deployment of nodes using stochastic geometry tools. The restricted-fronthaul capacity issue can be addressed by using caching techniques and downloading the cached content from the nodes when they are docked back or during off-peak hours, reducing the fronthaul traffic load. In studies [70], [71] studied optimal deployment of nodes using caching techniques.

4.7.2. Dynamic node deployment

There are several applications where the FANET nodes are deployed dynamically. One of the common deployment scenarios is where nodes serve the ground control stations as mobile access points. In this scenario, Marier *et al.* [72] presented an algorithm for calculating possible node losses under variable coverage area. To achieve high throughput with lesser energy consumption for a single UAV node and ground terminal, Zeng and Zhang [29] presents trajectory optimization. For restoration of services in disaster stricken area. Anazawa *et al.* [73] presents a genetic algorithm for node trajectory optimization. For a single node serving multiple ground terminals, trajectory optimization is suggested by [74] using space division multiple access. In studies [75], [76] studies for trajectory optimizations of FANET nodes are considered owing to the speed constraint. Mozaffari *et al.* [77] propose jointly optimizing 3D UAV placement, device-UAV association, and uplink power control to minimize IoT devices' transmit power. Chriki *et al.* [19] presented a comprehensive overview regarding the existing communications architectures recommended for the FANET networks.

Although there has been a lot of research work and several studies over the past few years on trajectory optimization of the FANET nodes, there are still open issues that need to be addressed and fixed, as explained by [19]. Especially for static deployments, optimal node locations cannot be ascertained for a particular number of nodes and spatial user density in a FANET application. Talking about the dynamic deployment modes, there is a great void in the analytical characterization of performance improvements from dynamic deployment; instead, most of the research work focuses on numerical trajectory optimization approaches. Moreover, several studies focus on trajectory optimization of a single node in one-dimensional space, keeping in view node speed, energy, and movement limitations instead of focusing on mobility cost, which impacts the FANET application in longer run.

5. COMMUNICATION ARCHITECTURE AND ROUTING IN FANET

One of the most important design aspects of the FANET is communications architecture and routing. A stable and comprehensive communication architecture is the key to the success of any FANET application. In this section, common communication architectures are discussed and reviewed alongside different available routing protocols and strategies [78].

5.1. Communication architecture

Communication architectures are responsible for the definition of procedures for communication between multiple FANET nodes and the ground control station. Yaliniz *et al.* [62] review various communication architecture models for efficient wireless connectivity. Communication architectures can be categorized into four basic arrangements. These categories are discussed as follows.

5.2. Direct communication

The simplest type of communication architecture that exists in FANET is a direct communication architecture. As explained in [11], a direct communication link is used between the FANET node (UAVs/drones) and the ground control station. In this architecture, communication between the nodes themselves is not possible, as it follows a centralized communication algorithm, which is why it cannot be applied in dynamic environments. This architecture is not robust, as there exists a single point of failure within the architecture in the form of the ground control station; if it fails, the whole application and mission are compromised.

5.3. Communication using satellite networks

With single UAV systems, where the communicating nodes are geographically separated into different regions, having direct communication or fixed communication infrastructure is not possible. Satellite networks can be utilized for communication between the nodes (UAVs/drones) and the ground control station, enabling each node to communicate with the ground control station individually using the satellite network. As explained by [19], there also exist some drawbacks of using this type of communication architecture, such as higher latency and transmission time and the hefty cost of leasing a satellite link. Transmission power is another problem, as the performance of this architecture directly depends on the transmission power of the ground station; also, for small UAVs, it is very challenging to fulfill such high-power demand. Since the satellite is a single point of failure, the architecture as a whole is prone to failure; also, the nodes need to be in direct line of sight for communication with the satellite network. If the application of the FANET demands UAVs to operate at low altitudes, obstacles like trees and buildings can compromise the communication.

5.4. Communication using cellular networks

Cellular networks are one of the most commonly used communication architectures these days. As in mobile GSM networks, in this type of architecture, the regions are split into different zones (cells), and each cell is served by a dedicated base station, and all the base stations are interconnected. Low-power transmitters are used in this type of communication architecture, making it possible to use an existing mobile operator's infrastructure, enhancing the range and mobility of the application. However, this type of communication architecture is difficult to implement in a disaster-stricken area where whole new infrastructure needs to be deployed and incurs a hefty cost. Azari *et al.* [79] provide a conclusive investigation of the scenario where a cellular network is serving UAV and ground users in the downlink. A network-UAV-based solution is developed, allowing integration of flying UAVs as a node into the cellular network.

5.5. Communication using ad hoc networks

This type of communication architecture is typically part of the MANET where the inter-node communication is done without the need for a central infrastructure. Each of the node is capable of communication and is considered an end system. All the nodes communicate with each other and relay information within the network. Constant changes in the topology of the UAV networks are addressed in this type of architecture. The beauty of this system is that even the ground control station is treated as a node, and the location of this node can be fixed or moving. The communication architecture in the FANET is further categorized into UAV-to-UAV and UAV-to-ground control station. With the collaboration of the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA), an initiative was launched in January 2017 to address challenges related to beyond LOS wireless communication between the nodes and the ground control station that may arise during different applications of the FANET, such as transportation and infrastructure surveillance. A comprehensive visual representation of all the discussed communication architectures has been presented in Figure 2.

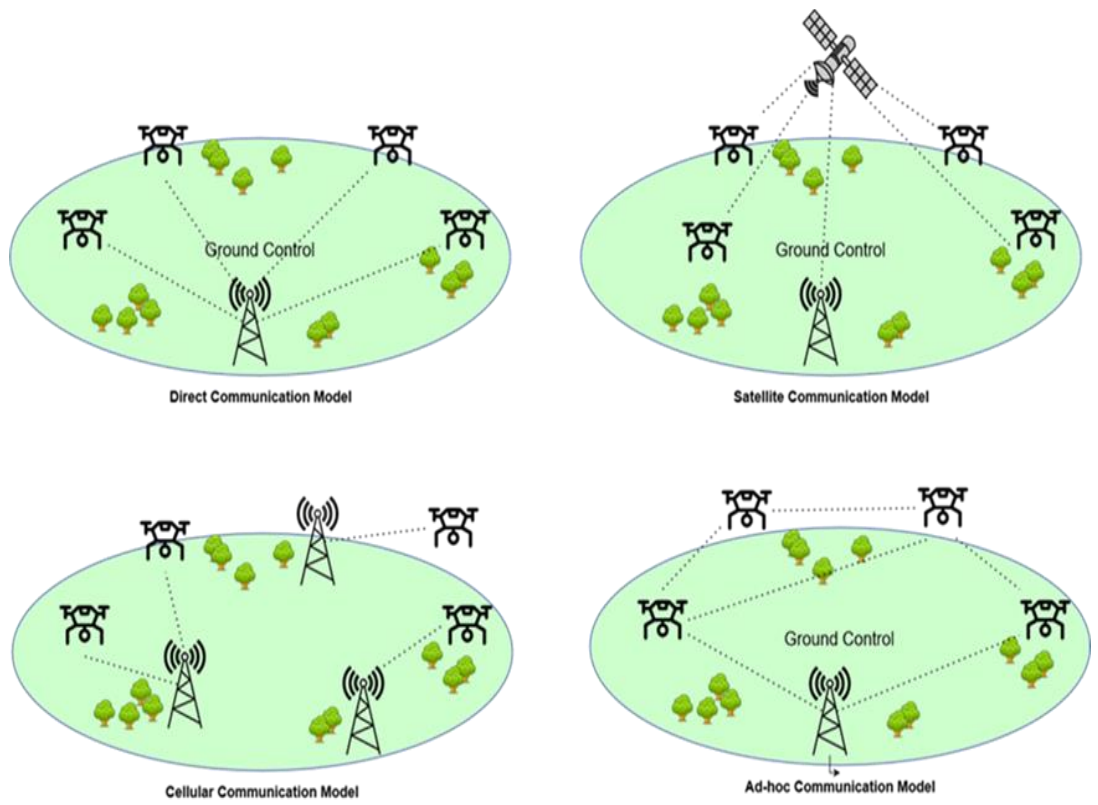

Figure 1. Communication architectures

5.6. Routing in flying ad hoc network

Although there are several advantages of the FANET communication architecture, routing remains a constantly challenging area, as the topology shift in the FANET is very dynamic [80]. Ad hoc networks were proposed by [79], [81]. Since FANET is derived from the MANET and VANET protocols, protocols affiliated with these networks were tested for the FANET, but due to the different nature of nodes, such as rapid speed and link shifts and less available power in FANET, the existing MANET and VANET routing protocols are not capable of satisfying the specific application needs for the FANET. Khan *et al.* [82] proved that AntHocNet may perform better as compared to other protocols. Therefore, changes are required to these protocols to satisfy the FANET application needs. Usman *et al.* [83] emphasized the appropriateness of routing protocol design for successful data communication in the FANET. A taxonomy of available routing protocols for ad hoc networks is presented from the literature rather than listing all of them for better understanding. Ali *et al.* [84] recommend a routing method called greedy-optimized link state routing (G-OLSR) for drone networks (FANETs). It helps drones communicate and work together more efficiently. It also automatically adjusts when the network changes.

5.6.1. Static routing protocols

These type of routing protocols is used where the nodes communicate with a specific number of nodes or a ground control station. A pre-computed static routing table is loaded before starting the mission, and there's no need to update it during the mission [85]. These protocols are not fault-tolerant since the changes can only be applied before the start of the mission or when the mission is finished and are not suitable for dynamically changing networks. Leonov and Ryabchevsky [86] review the performance evaluation of the optimized link state routing protocol (OLSR). The practical implementation of this type of routing protocol is limited for FANET applications.

Load carry and deliver (LCAD) is considered the first routing model for the FANET [87]. The main purpose of this protocol is to maximize throughput and increase security, which is achieved by loading data into a node from the ground control station; then the data is flown to the destination and then back to the ground control station. Transmission time is higher in LCAD since the data is carried by a single UAV, but ultimately it achieves higher throughput. This type of protocol can be used for bulk data transmission applications where transmission delays and latency can be acceptable.

Scalability is another concerning challenge in the FANET application; multi-level hierarchical routing (MLHR) addresses this problem by organizing the UAV network hierarchically where there's a need for several clusters serving in different areas [88]. For every UAV cluster, there's a designated cluster head (CH) which controls and represents the cluster, and each cluster is capable of performing different tasks. CH is typically in communication with all the nodes within the cluster and the ground control station, so the CH needs to be in direct communication with the ground control station to relay information within the cluster. This protocol is suitable when a large number of nodes are involved in the application, and the area to cover is vast. Wireless communication in ad hoc networks can support both one-to-one and one-to-many communication modes. When several nodes are requesting data in a FANET application, and data is served by an on-demand algorithm, the data-centric routing (DCR) [88] protocol is used. This protocol can be practically applied where there is a small number of nodes involved with a fixed trajectory. This routing protocol can also work well within a clustered model.

5.6.2. Proactive routing protocols

Before transmission of data packets, these routing protocols store routing information about all nodes within the network in a table. In the event of a topology change, the routing table needs to be updated, making the updated routing information available for path selection by the transmitter and receiver. There also exist some challenges for this type of routing protocol due to extensive message communications between the nodes; the effective use of bandwidth is a challenge, and the response time is slower in case of topology change or a node failure. As discussed by [89], these protocols do not support the FANET application involving networks with highly mobile nodes and a larger number of nodes.

A new forwarding mechanism was introduced to reduce communication overhead by [90] as directional optimized link state routing (DOLSR) for FANETs having nodes with directional antennas installed. This protocol was derived from OLSR [91] used in the MANET. The destination distance is first tested by the node, and if it is greater than the max achievable distance by a directional antenna, DOLSR is selected for routing; if it is less than the max achievable distance OSLR is used where there is availability of omni directional antenna and if the antenna is not available it is reverted to DOLSR. For better performance, multipoint relay is used to achieve lower communication overhead and less delay. Rosati *et al.* [92] introduced speed-aware predictive-OLSR to help the protocol by adding GPS information in the model. Contention-based OLSR was introduced by [93]; this model involves network-MAC-physical cross-layer design for overall performance enhancement of the FANET application.

5.6.3. Reactive routing protocols

In this class of routing protocols, the routes are published on a need basis, such as when a node in the FANET wants to communicate with other nodes [94]. Communication overhead issues that exist in proactive routing protocols can be addressed in this reactive routing protocol class. The route request message type is sent by the transmitters using a flooding technique for path scanning to all the neighboring nodes; all the nodes in the network work on the same principles until the message has reached the receiver node. On the other hand, the route reply message is created and relayed by the destination node to the source node by unicasting. With these techniques, the need to update all the routing information in the tables is not required further, as all nodes store information about the current route being used.

Several reactive routing protocols have been proposed for FANETs over the past few years. For example, based on AODV, time-slotted AODV [95] and reactive greedy reactive (RGR) protocols [96] were proposed. Packet delivery is ensured by Time-slotted AODV by allowing one node to transmit data at a time, hence avoiding packet collision. RGR combines the reactive routing method of AODV with greedy geographic forwarding (GGF). Tropea *et al.* [97] evaluated two approaches in the agriculture domain for killing parasites, one based on proactive management of topology (link-state routing strategy (LSRS)) and the other based on a reactive approach (reactive forwarding strategy (RFS)). The results depict the reactive approach to be most optimal for this kind of application in the agriculture domain.

5.6.4. Hybrid routing protocols

To overcome shortcomings of both reactive and proactive routing protocols, a hybrid approach is used to introduce where the feature sets of both proactive and reactive routing protocols are combined to form hybrid routing protocols. Using hybrid routing protocols, two main challenges of proactive and reactive routing protocols can be addressed, i.e., control message overhead from proactive routing and initial delay in the route discovery process. From the scalability point of view, this type of protocol is suitable for large network deployments, where the zones are formed to distribute the network and proactive routing protocols are responsible for intra-zone routing and reactive routing protocols are responsible for inter-zone routing.

Zone routing protocol (ZRP) [98] is one of the example for hybrid routing protocol and is based on the zones concept. Each of the node is considered to have its own zone with a predefined radius. So, in the FANET application, the zones in this routing protocol intersect. The intra-zone routing is managed by a proactive method. When the source and destination lie within the same zone, relaying of information can be started instantly. When the source and destination lie in different zones, inter-zone routing is done by a reactive method. Temporarily ordered routing algorithm (TORA) [99] is another hybrid routing protocol. It uses mostly a reactive routing protocol but also involves some proactive routing protocol. A directed acyclic graph (DAG) is formed and secured from the source to the destination node. Shortest paths are not always used by TORA; instead, it can use longer paths to reduce network overhead. Khan *et al.* [20] present a hybrid wireless communication scheme required the low-power consumption capable of transmitting data as higher utilizing Wi-Fi technology. Nadeem *et al.* [100] highlight critical research challenges in the FANET and present comparative analysis of routing strategies along with review of suitability of ad hoc routing protocols.

5.6.5. Geographic routing protocols

These are the type of protocols where the geographical information of nodes is pre-determined, and this geo information is utilized for the calculation of best route from source to destination. Greedy perimeter stateless routing (GPSR) [101] is one of the example of this type of routing protocol, where each node tracks its neighboring nodes by beaconing at specified intervals. Node locations are used to forward packets to geographically nearest node to the destination. GPSR is one of the earliest proposed protocols, and on its basis several approaches and protocols have been developed in recent years. Mobility prediction geographic routing (MPGR) [102] is one of the protocol based on GPSR; it enhances GPSR routing protocol by addition of mobility prediction for nodes, reducing the effect on the communication overhead caused by highly mobile nodes. Another protocol that is based on GPSR is UAV search mission protocol (USMP) [103]; it employs two cross-layer features for improvement in routing process, i.e., location update and waypoint conflict resolution to identify node locations that have not been scanned yet and node collision avoidance, respectively. In studies [104], [105], adaptive beacon position prediction (ABPP) was proposed, which is an adaptive beacon scheme it can dynamically adjust beacon frequency for prediction of future UAV positions. The proposed scheme can effectively improve the packet delivery ratio by decreasing beacon overhead.

A continuous Hopfield neural network was used route optimization for high-speed movement of the UAVs on the basis of dynamic source routing (DSR) protocol by [106]; the simulation result for the optimized DSR showed significant improvement for end-to-end average delay, throughput, and packet delivery ratio. A comprehensive survey of position-based routing protocols with various categories was performed by [107]. A detailed description and taxonomy of these protocols was included in this survey.

These are only few routing protocols discussed from the literature; study [24] presents a comprehensive comparison of routing protocols along with challenges and issues in the respective classes, and a taxonomy for the different categories of routing protocols is shown in Figure 3.

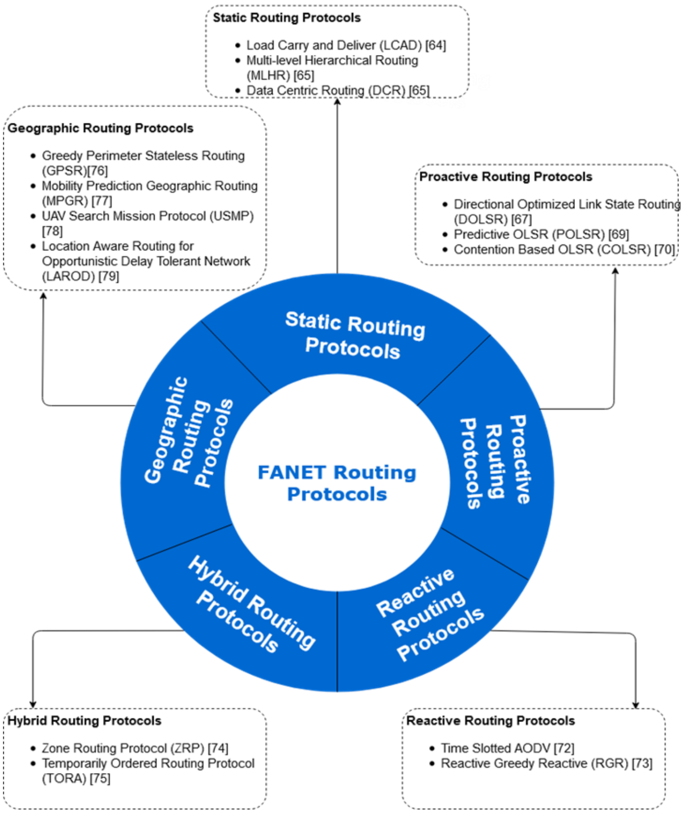

Figure 2. FANET routing protocols taxonomy

6. FANET CHALLENGES

Although FANETs have several similarities with their alpha family MANETs and VANETs, such as networking and communication in an ad hoc fashion using mobile devices. Srivastava and Prakash [108] discussed concurrent issues and challenges. FANETs have some unique features and characteristics, which open up some unique additional challenges owing to the nature of FANETs. Singh and Verma [109] have discussed the fundamental concepts of FANETs and explained the various challenges. From the literature, this study can categorize six types of challenges that exist for FANETs, described in the subsequent subsections.

6.1. Routing challenges

Due to the high-speed movement of nodes in the FANET and rapid topology changes, the connectivity between the nodes and the ground control station can be a very challenging issue. Oubbati *et al.* [110] have performed a very comprehensive and extensive survey on available routing technologies along with the constraints, challenges, and open research issues in the FANET. The nature of links in several FANET applications is intermittent due to rapid shifts in location and speed, and nodes can extensively join and leave the network owing to the nature of nodes. Several other variables and environmental constraints, like mountains, weather conditions, and terrain uncertainties, can cause rapid topological shifts. Keeping in view these variables, designing a comprehensive and efficient routing protocol is a challenging task. Although existing researches have been showing improvements and promising results by offering improved and more adaptive routing protocols that are capable of quick deployments and recovery, autonomous and robustly lower processing overheads.

6.2. Security challenges

Owing to the special features of FANETs, they are typically insecure and need extensive work and a comprehensive framework for securing the network; mainly, the nature of the FANET itself is the cause of existing security vulnerabilities, as explained by [19]. Seven security challenges typically exist for FANETs, i.e., authentication for node inclusion into the network and message authentication. Data integrity and consistent message delivery along the whole path inside a FANET. Confidentiality to ensure privacy so that only authorized nodes can access the data: i) identity should be anonymized in the communications for FANET so that the real identity of the users or nodes are not compromised in case of eaves-dropping and sniffing attach; ii) availability of the nodes and services offered by the FANET to be ensured all times during an application; iii) timely delivery and relay of information should be ensured to avoid man in the middle and spoofing attacks; and iv) should be sustainable and have autonomous recovery capability for the FANET communication networks to recover automatically in case of an attack without any human involvement.

Mowla *et al.* [111] proposed an adaptive federated reinforcement learning-based jamming attack defense strategy by developing a model-free Q-learning mechanism with an adaptive exploration-exploitation epsilon-greedy policy, including an on-board federated jamming detection mechanism. Due to rapid connection and disconnection of nodes, secure routing is another security challenge in the FANET. Following are the common security attacks that exist for the FANET networks: i) multi-layered attacks: denial of service (DoS), impersonation, replay, man-in-the-middle attack (MIMA); ii) physical layer: intervention, jamming, snooping; iii) data link layer: disruption medium access control (MAC), bandwidth stealing, traffic monitoring, wired equivalent privacy (WEP) weakness; iv) network layer: black holing, spoofing, worm-hole, route tracking, massage fabrication; v) transport layer: session hijacking, SYN flooding: and vi) application layer: repudiation, data corruption.

6.3. Quality of service challenges

The FANET applications involve different types of data including GPS coordinates and data, plain text data, images, video and audio streaming, and bulk data transfer. All the different types of data have different service and performance requirements, which is difficult and challenging to offer in fast-moving, highly mobile, and frequently adding and removing FANET nodes [112]. Managing delay, bandwidth, jitter, and packet loss for specific applications of FANET is another challenge.

6.4. Mobility challenges

Appropriate placement and movement of nodes in FANET networks is one of the major research topics and challenges in FANET networks. Nodes with different architectures and capacities are used for different FANET applications. Smaller drones and UAVs cannot carry huge payloads and can only support fewer payloads and equipment on board, which is a very challenging issue owing to the dynamic application range of the FANET. Selection of a suitable mobility model is another challenge. As explained in the earlier section, several mobility models exist, and there has been a lot of research in this area, but still selection of a suitable mobility model for ever-changing and dynamic FANET applications is a challenging task.

6.5. Scalability and data delivery challenges

The number of nodes in a FANET network contributes towards the accomplishment of tasks quickly and efficiently. But scaling the FANET networks is a challenging task; if, during a mission, a few nodes go out of order and need to be excluded, it would directly impact the mission and may even compromise it, therefor it is required to add new nodes into the FANET network to effectively complete the mission. The FANET application should be adaptive and designed on the principle of scalability so that it can support a reasonable number of nodes, which is critical to mission success. On the other hand, the FANET nodes relay very important data and information, and timely delivery of which is critical for completion of any task and mission. Ensuring a reliable network for effective data delivery within the FANET nodes and the ground control station is another challenging task.

6.6. Environmental challenge

The FANET is prone to environment variable, and the nodes require a specific environment to operate. Difficult and harsh weather conditions like snow, hail storms, sand storms, fog, smoke, and lightning are some of the environmental constraints that impact the performance and reliability of the FANET networks. The environmental conditions need to be in a specified range for the FANET nodes in order to effectively operate and complete the missions. This is one of the most challenging aspects in FANET applications as some of the constraints are unavoidable, and a very fault-tolerant and resilient algorithm and arrangement is required for effective use of a FANET.

6.7. Real-world implementation challenge

The FANET is a relatively new field of research study, and there have been a lot of research in different areas of FANET. While reviewing different research articles, it was observed that most of the research on FANET is based on simulations, and its results and the practical aspects are being overlooked; the results from simulated research and practical real-world research may be different. This is one of the key aspects in the adaptability and future evolution of FANET technology and requires more focus towards the practical research to identify and address the real-world challenges in FANET technologies.

7. CONCLUSION

Over the past few years, the importance and practical applications of FANET have been witnessed, making it very crucial in different commercial and research-based complex applications. Good connectivity, improved security, effective routing, carefully selected mobility model, and architecture of FANET nodes are key for obtaining optimal results. With a comprehensive review of literature related to FANET applications, mobility models, trajectory optimization, communication architectures, routing, and challenges, it has been concluded that the selection of the most optimal parameter depends on the application of FANET. Selection of the most appropriate mobility models, trajectory optimization, communication architectures, and routing protocols varies from application to application, whereas the challenges are also application-specific. These issues and challenges are still an open research area in this domain and need further experimentation and research to address. The goal of this research is to lay down a comprehensive base for addressing the challenges and encourage future research for the development of a dynamic model for identification of the most appropriate parameters of FANET to achieve maximum efficiency and fault tolerance. To address the limitations, it is recommended that future research should validate findings using real UAV networks. It will be helpful to test the models under real-world conditions. A detailed security analysis should be included, focusing on threats, cryptographic methods, intrusion detection, and secure routing. Moreover, application-specific case studies in areas like military, disaster response, and environmental monitoring will provide understanding of the specific needs of different sectors.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The simulation files/data used to support the findings of this study are available from the corresponding author, [MA], upon request.

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