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Review

Topology-Based Routing Protocols and Mobility Models for Flying Ad Hoc Networks: A Contemporary Review and Future Research Directions

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Abstract: Telecommunications among unmanned aerial vehicles (UAVs) have emerged recently due to rapid improvements in wireless technology, low-cost equipment, advancement in networking communication techniques, and demand from various industries that seek to leverage aerial data to improve their business and operations. As such, UAVs have started to become extremely prevalent for a variety of civilian, commercial, and military uses over the past few years. UAVs form a flying ad hoc network (FANET) as they communicate and collaborate wirelessly. FANETs may be utilized to quickly complete complex operations. FANETs are frequently deployed in three dimensions, with a mobility model determined by the work they are to do, and hence differ between vehicular ad hoc networks (VANETs) and mobile ad hoc networks (MANETs) in terms of features and attributes. Furthermore, different flight constraints and the high dynamic topology of FANETs make the design of routing protocols difficult. This paper presents a comprehensive review covering the UAV network, the several communication links, the routing protocols, the mobility models, the important research issues, and simulation software dedicated to FANETs. A topology-based routing protocol specialized to FANETs is discussed in-depth, with detailed categorization, descriptions, and qualitatively compared analyses. In addition, the paper demonstrates open research topics and future challenge issues that need to be resolved by the researchers, before UAVs communications are expected to become a reality and practical in the industry.

Keywords: unmanned aerial vehicle; multi-UAV network; flying ad hoc network; topology-based routing protocols; mobility models

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1. Introduction

Unmanned aerial vehicles (UAVs), commonly known as drones, have grown in popularity in recent years as a result of the rapid deployment of technology solutions such as low-cost Wi-Fi radio communication, GPS, sensors, and integrated devices. They are now widely used in academic research, civilian domains, and military applications [1].

UAVs are utilized for a range of military purposes, including reconnaissance [2] and secure communication protocol in military operations [3]. Further, they can be employed in civil applications such as relief operations in disaster environments [4], search and rescue [5], surveillance and monitoring [6], video surveillance mission in smart cities [7], and civil engineering structures [8]. Moreover, UAVs are used in emerging applications such as intelligent transportation systems [9], smart healthcare [10], package delivery [11], 5G communication [12], and mobile edge computing [13]. UAVs can also be adopted in agriculture operations such as precision agriculture [14], imaging platforms for vegetation analysis [15], and thermal study in a rural environment on a dry-stone landscape [16]. Figure 1 shows some UAV applications that can be applied in industry and consumer markets.

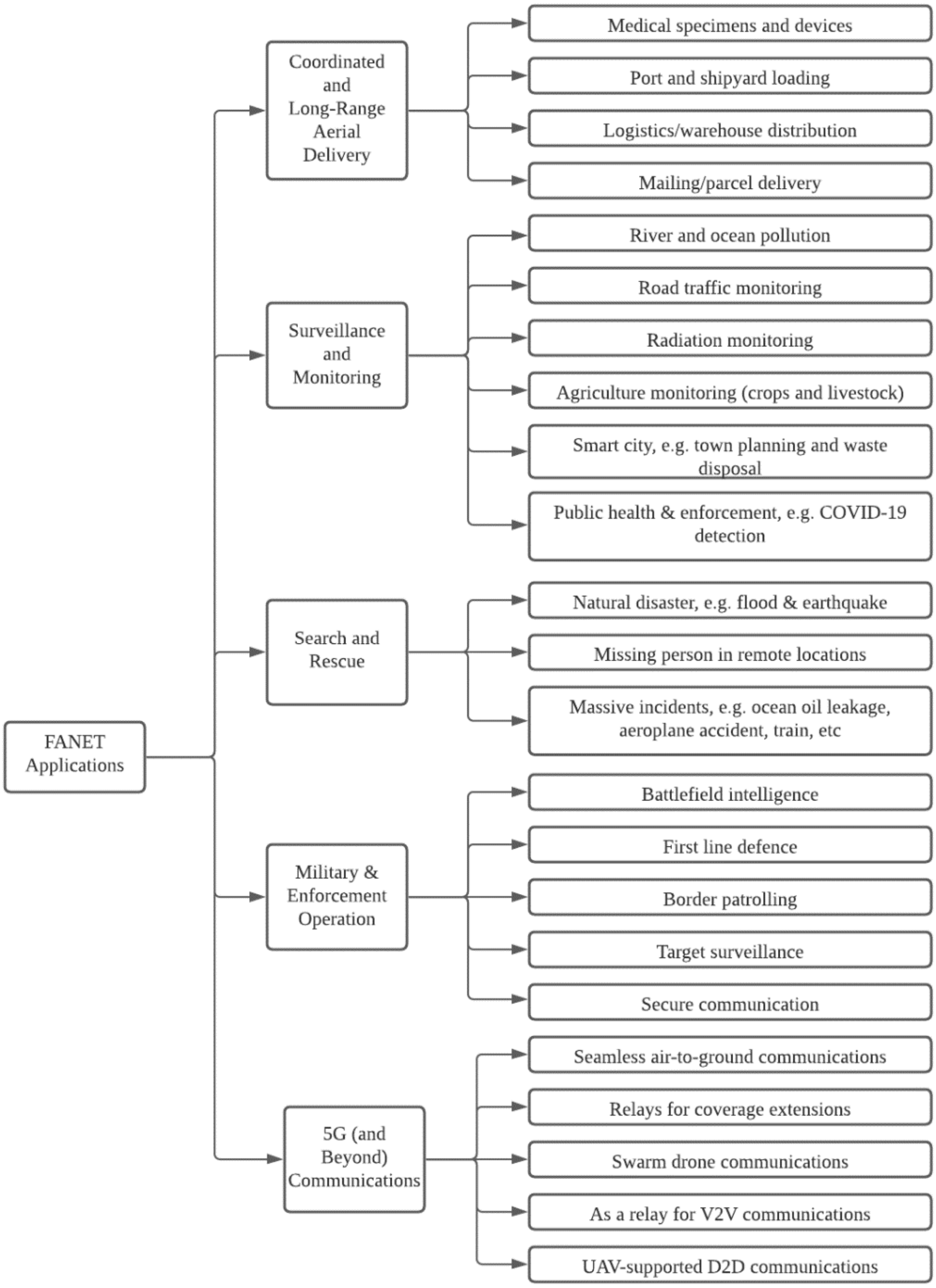

Figure 1. Potential of FANETs in various unmanned aerial vehicles (UAVs) applications.

UAVs may operate with varying levels of automation, whether remotely directed by a ground station operator or directed by a completely autonomous embedded controller, and they can be readily deployed in a network. As illustrated in Figure 2, UAV networks may be categorized into single and multi-UAVs. A single-UAV network is most commonly a large unmanned aerial vehicle (UAV) that is connected directly to a ground control station and/or satellite network. This type of network has been frequently employed to carry out specific missions. This UAV must be installed with complicated hardware communication technologies to maintain connectivity with the ground control station. If the UAV fails, the operation will be terminated [17].

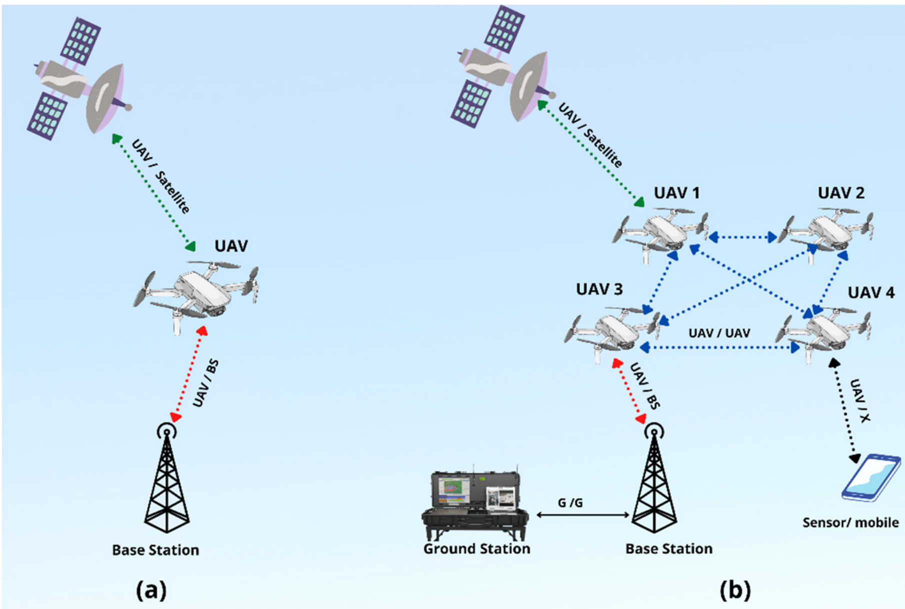

Figure 2. (**a**) Single-UAV network; (**b**) multi-UAV network.

In a multi-UAV network, multiple UAVs are connected to one another, on top of a base station, sensors, and satellite. In terms of survivability, dependability, mission completion time, and redundancy, a multi-UAV network surpasses a single-UAV system, which implies that even if one of the UAVs fails during an operation, the operation may be completed with the other UAVs [18]. Moreover, in multi-UAV networks, UAVs may well be arranged in a variety of topologies as needed. Furthermore, the connection coverage of a multi-UAV platform may be easily adjusted by increasing additional UAVs to the network [19]. This network of multiple UAVs is often referred to as a flying ad hoc network (FANET), where many UAVs must collaborate and cooperate via an inter-UAV radio communication interface [20]. On the other hand, developing a reliable communication framework for multi-UAV systems is a complex challenge.

In FANETs, there are five different types of communication links: UAV-to-ground base station link (UAV/BS), ground base station-to-ground base station link (G/G), UAV-to-UAV link (UAV/UAV), UAV-to-satellite links (UAV/Satellite), and UAV-to-sensor device links (UAV/X). UAV/BS communication connections send data from a UAV in the air to a ground base station, such as real-time video or pictures. G/G connections allow several ground base stations to communicate and share information with each other. UAVs can function in ad hoc communication in UAV/UAV, where they must interact with one another to reach a consensus and share data. UAV/Satellite provides a communication link between UAV and satellite at high altitudes. Finally, the UAV/X link gathers information from sensors or mobile devices on the ground.

A routing protocol is necessary for data transfer between UAV nodes. Traditional ad hoc network routing protocols designed for VANETs and MANETs are often inadequate to suit the demands of FANETs [21]. FANETs have unique characteristics that make developing reliable routing protocols challenging, such as flying in three dimensions, high mobility, low node density, rapid topology changes, often-severed links, network segmentation, and limited resources [22]. However, UAV can cooperate with VANETs to assist the process of routing data packets to meet constraints of delay and minimum overhead [23] and also detection of malicious vehicles attacks [24]. Additionally, several FANETs applications have various quality of service (QoS) requirements that need to be adjusted. Although several applications such as data collecting and mapping can tolerate delays, others, such as monitoring and tracking, and search and rescue (SAR), need real-time data flow with minimal delays. Consequently, various studies have been conducted to design routing protocols that consider application requirements and the specific properties of FANETs. These are either novel routing protocols [25] or updates to existing ad hoc routing protocols [26].

Several reviews have discussed the different FANETs routing techniques [27–35]. Table 1 summarizes the key contributions and limitations of these reviews. The difference in this study is that it covers modern topology-based routing protocols designed specifically for FANETS, which are not covered yet in the literature. In this study, the latest state-of-the-art developments in relation to the primary features, limitations, routing method, and application scenario for the routing protocols are covered. To pursue these objectives, an attempt was made to integrate many thoroughly examined and thought-provoking solutions of FANETs routing techniques to achieve precise and concrete deduction for interested researchers. The major contributions to the knowledge of this study are summarized as follows:

1. An in-depth look into existing topology-based routing protocols in FANETs. A review and comparison of topology-aware routing protocols explicitly designed for FANETs with other studies considering classical rioting protocols is presented.
2. Topology-based routing protocols classification for FANETs using the fundamental routing mechanisms. There are 22 topology-based routing protocols studied and described, both existing and recent.
3. The reviewed topology-based routing protocols are compared qualitatively on the main features, routing mechanism, limitations, mobility models, simulation tools, performance parameters, and application scenarios. Existing studies do not consider all these parameters in comparative analysis. Moreover, engineers and researchers may find this comparison useful in deciding which topology-based routing protocol is appropriate for their needs.
4. The most critical research challenges and issues in developing a topology-based routing technique for FANETs are updated based on this field's current active research progress.

Table 1. A summary of current FANETs routing protocol review articles.

Reference/ Year of Publication	Routing Protocols	Comparison Analysis of Routing Protocols	Routing Challenges	Taxonomy of Mobility Models	Comparison Analysis of Mobility Models	Communication Links of FANET	Open Issues
Ref. [27]/2014	√	X	X	X	X	√	√
Ref. [28] 2017	√	√	X	X	X	√	√
Ref. [29] 2019	√	√	√	X	X	√	√
Ref. [30]/2018	√	X	X	X	X	√	√
Ref. [31]/2019	√	√	√	X	X	X	√
Ref. [32]/2019	√	√	X	X	X	√	√
Ref. [33]]/2020	√	X	√	X	X	√	√
Ref. [34]/2020	√	√	X	X	X	√	√
Ref. [35]/2021	√	√	X	X	X	X	√
This review	√	√	√	√	√	√	√

2. Mobility Models in FANETs

The FANETs mobility model describes the motions of UAVs in a specific region over time, including changes in speed, direction, and acceleration. Due to their mobility, UAVs may be tailored to the specific needs of an application, leading to better performance and flexibility. The study of node motion can be carried out by simulation or mathematical modeling. The simulation method can realistically emulate the actions of UAVs to obtain as realistic results as possible just before actual deployment and provides a better solution for complex problems. The existing mobility models that can be used for UAVs can be categorized as random, group, time-dependent, and path-planned models. Figure 3 illustrates the taxonomy of the mobility model in FANETs.

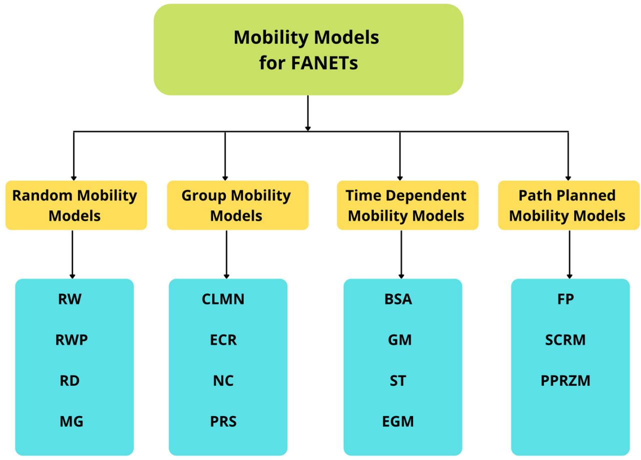

Figure 3. Taxonomy of mobility models in FANETs.

2.1. Random Mobility Models

The most popular models used in network research are randomized mobility models. They depict a group of movable nodes with independent actions that can be easily implemented with several models. However, these types of mobility models were unable to properly replicate the actual behavior of the UAV due to the abrupt changes in the UAV's speed and direction, as well as considering only two-dimension movement.

2.1.1. Random Walk

The Random Walk (RW) mobility model [36] was created to accommodate the unpredictability of many natural things' movements. The mobile nodes in RW imitate the erratic motion by selecting a random direction and speed each time. Each movement takes place over a fixed time interval or a fixed distance before a new speed and direction are calculated. The new direction of a node travelling to the simulation area's edge is determined by the introduced direction. RW is a memoryless mobility model since it does not save information about its prior speeds and locations. Figure 4 depicts an example of an RW motion. The RW model may be adopted in several FANETs missions and protocols, including an increase in coverage area [37] and enhancing UAV relay service [38].

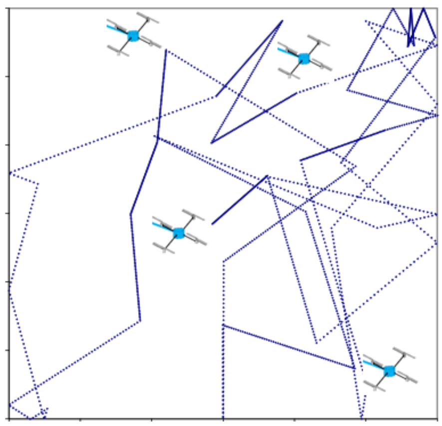

Figure 4. The trajectory of FANETs using RW models.

2.1.2. Random Waypoint

The Random Waypoint (RWP) [39] mobility concept functions similarly to RW, but with a certain number of extensions. For a length of time, a mobile node is stationary. The node selects a random destination and speed when the timer runs out. A mobile node subsequently travels at the preset speed in the direction of the newly chosen destination. Whenever the mobile node reaches its destination, it takes a little break before proceeding with the operation. The presence of a halt interval and choosing a random destination rather than a direction distinguishes RWP from RW. The RWP model may be used in FANETs relaying network applications because of its past-time characteristics [40]. Figure 5 depicts an RWP mobility pattern for FANETs. The UAV movement pattern is centered in the simulation area's center. Despite the presence of pause times, they aid in smoothing unexpected changes in direction. A progressive increase or decrease in speed is necessary for UAVs.

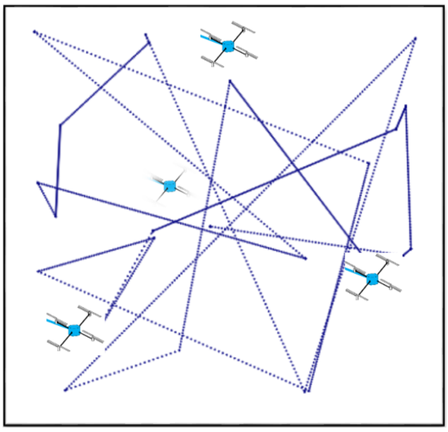

Figure 5. The trajectory of FANETs using RWP models.

2.1.3. Random Direction

As a result of the increased possibility of moving to a new location near the simulated area's center, the Random Directions (RD) [41] model was designed to deal with concentration of nodes on the central area of the RWP mobility model. RD chooses a destination place on the simulation area's boundaries with every mobile node. Once it is on the boundaries, it stops and chooses a new random destination location again. The FANETs mobility pattern in RD is shown in Figure 6. Even in RD, we have the same unexpected motion feature, similar to that of RW and RWP. RD mobility model was implemented in FANETs in [42]; however, the RD model was shown to exhibit unrealistic movement characteristics similar to those of RWP.

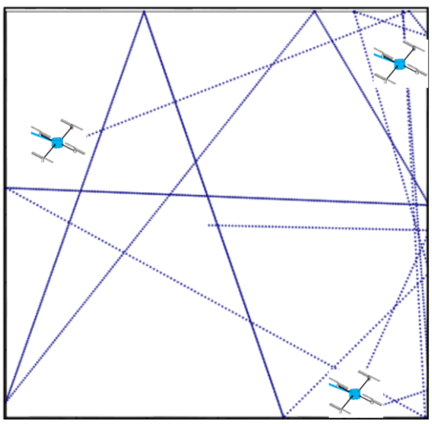

Figure 6. The trajectory of FANETSs using RD models.

2.1.4. Manhattan Grid

The Manhattan Grid (MG) model employs a grid road structure [43]. This mobility model was designed to simulate vehicle movement in an urban environment with a well-defined street layout. Mobile nodes move horizontally or vertically across an urban map. The MG model employs a random approach to node movement selection since a vehicle must choose whether to continue driving in the same direction or turn at each intersection, as shown in Figure 7. UAVs can follow the same direction as ground nodes to complete a mission under such a mobility model [40], and also this model is also adopted in UAV-assisted mmWave 5G operation in urban environments [44]. Moreover, the MG model can be adopted in FANETs industry applications, such as the mining industry [45].

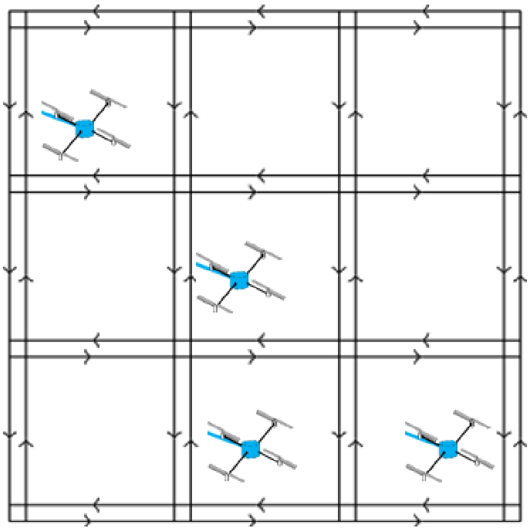

Figure 7. The trajectory of FANETs using MG models.

2.2. Group Mobility Models

Group mobility models contain a geographic limitation for all mobile nodes. Every one of the mobility models shown in the preceding sections imitates the behavior of mobile nodes that are entirely self-contained. Nevertheless, with FANETs, there are several scenarios in which UAVs must fly together to pursue a common point, resulting in spatial dependency. This kind of grouping is typically used to accomplish a specific task. The group mobility models are suitable for particle swarm of FANETs [46].

2.2.1. Column Mobility Model

Each node in the Column (CLMN) mobility model [47] revolves around forward-moving a reference point on a specified line. Specifically, every mobile node in a CLMN model rotates around the point of reference at random speed and direction. Figure 8 shows an example of two UAV trajectories following CLMN. These models' spatial constraints can ensure that UAVs in each group stay connected while also preventing collisions. The CLMN mobility model can be applied for agricultural management or scanning application scenarios, where UAVs start flying in a specific area to scan for a specific target. Whenever one of the UAVs spot the target, it starts to transmit data to a base station through other relaying UAVs [48,49].

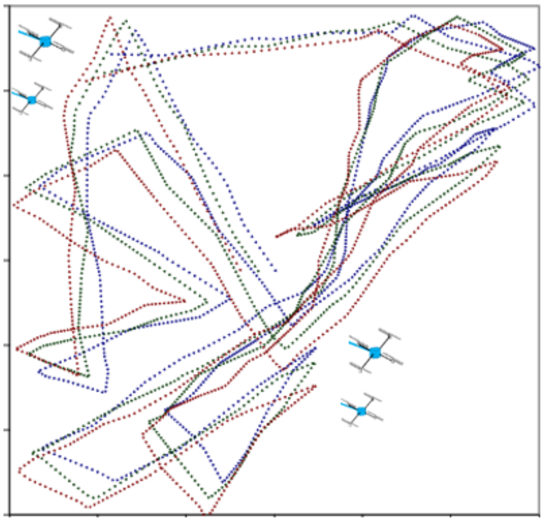

Figure 8. The trajectory of FANETSs using CLMN models.

2.2.2. Exponential Correlated Random

Exponential Correlated Random (ECR) [50] is described as a group of mobility models that depicts correlated dynamic motion of a group of nodes. ECR employs the motion function to model all of the group's conceivable movements to control it. This is accomplished by predicting the group's new placements in the next available timeframe, as shown in Figure 9. ECR model could be used in conjunction with FANETs to control and avoid collisions among a large group of UAVs [51]. The ECR model can be adopted in mobility-aware connectivity of 5G cellular networks [52].

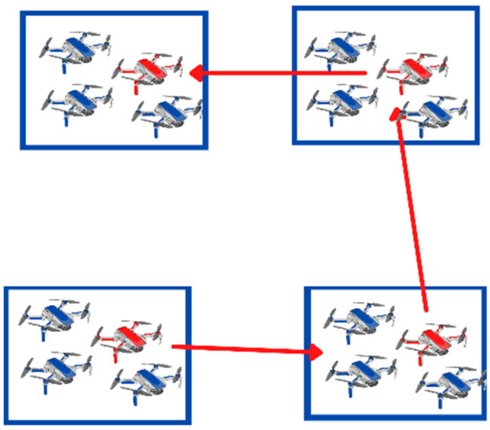

Figure 9. The trajectory of FANETs using ECR models.

2.2.3. Nomadic Community

In the Nomadic Community (NC) mobility model, every mobile node moves randomly around a certain reference point [53]. Unlike CLMN, a set of nodes shares the same space determined by a singular reference point. Figure 10 shows an example of two nodes following the path of NC. Furthermore, there are nodes in NC that share similar locations, resulting in UAV collisions. In order to partition the flying areas, in the beginning, additional limitations might be applied to the updated versions of this mobility pattern. This mobility model is easily adaptable to agricultural and multi-UAVs in military battlefield environments [54].

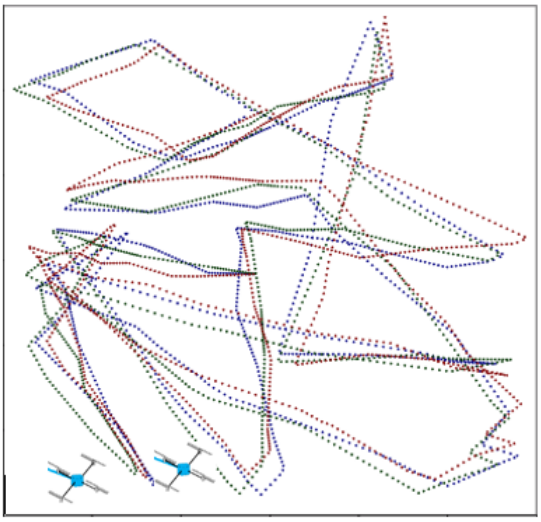

Figure 10. The trajectory of FANETSs using NC models.

2.2.4. Pursue Mobility Model

The Pursue (PRS) model seems similar to the concept of the NC mobility model [55]. The nodes in this environment attempt to track a particular object travelling in a specific way. During a pursuit of the target, the mobile nodes move in a random relative motion. UAV movement utilizing PRS is depicted in Figure 11. Moreover, to keep an accurate track of the subject being pursued, each mobile node's random behavior is restricted. For example, in the context of smart vehicles, whenever a collection of unmanned aerial vehicles tracks a suspect vehicle across a city, PRS could be used [55].

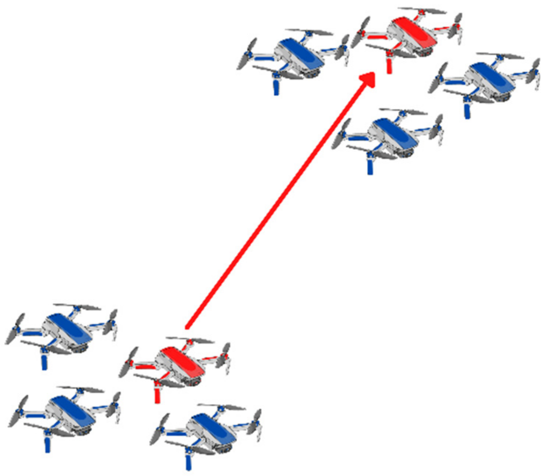

Figure 11. The trajectory of FANETs using PRS models.

2.3. Time-Dependent Mobility Model

This type of mobility model tries to prevent sudden changes in speed and direction. Under this model, UAV movements are determined by various mathematical equations and several parameters, including the current time, prior directions, and speeds. For a smooth updating of motion, all of these parameters are considered.

2.3.1. Boundless Simulation Area

The Boundless Simulation Area's (BSA) mobility concept is built on a relation among previous speed and direction and the current ones [56]. Every period, speed and direction qualities are updated every cycle, resulting in a smooth change of motion. Whenever a mobile node gets to one side of the simulation area, it keeps moving until it reaches the opposing side, which is performed uniquely compared to other models. Figure 12 depicts UAV movement using BSA, and the point density changes smoothly, as can be seen. Additionally, BSA lets mobile nodes move throughout the simulation area without inhibiting and deleting all simulation evaluation edge effects. In FANETs, this model is not extensively used [48].

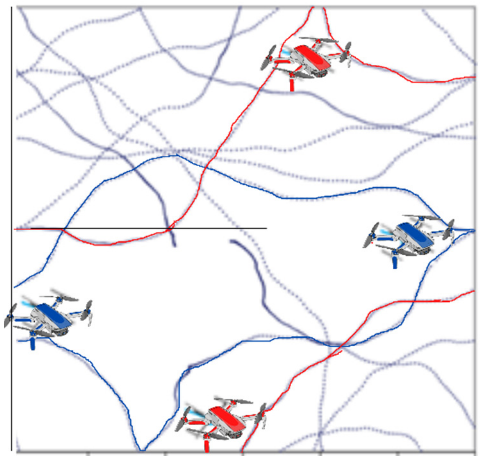

Figure 12. The trajectory of FANETs using BSA models.

2.3.2. Gauss Markov

The Gauss Markov (GM) model [57] is a mobility model based on the time that adjusts for different levels of randomness using multiple parameters to minimize sudden movement changes. As shown in Figure 13, any node is first given a current direction and speed, and its coming travel is then updated and specified depending on its prior direction and speed. As a result, GM could avoid the abrupt turns and stops that were observed in models based on random patterns. The equations system connects previous directions and speed to upcoming ones, allows for seamless updating if the right settings are used for parameters. GM is adopted to communicate among UAVs in various applications scenarios, such as those found in [58,59].

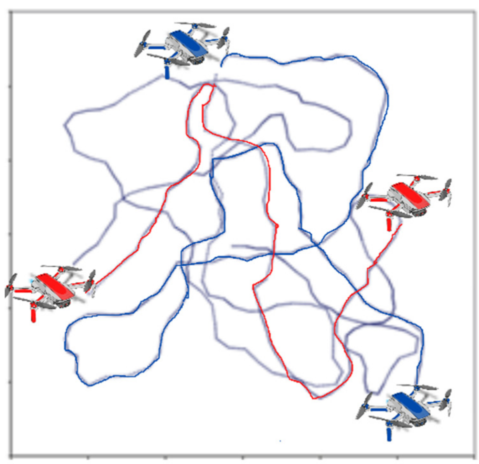

Figure 13. The trajectory of FANETs using GM models.

2.3.3. Smooth Turn

The Smooth Turn (ST) model enables nodes to travel in various directions while maintaining a connection between their acceleration in spatial and temporal variables [60]. In ST, every UAV selects a location in the flying sky and revolves about it until it finds a new turning point. Moreover, to achieve a smooth trajectory, it chooses a point that is perpendicular to the UAV's direction. The waiting time interval is exponentially distributed, according to the model. Figure 14 illustrates the trajectory of this mobility model. Without adding any additional constraints, ST accurately depicts the smooth movement patterns of UAV aircraft. ST model is designed to support FANETs monitoring operation [61]. Further, it can be used in the Internet of Things (IoT) integrated with UAV Networks [62].

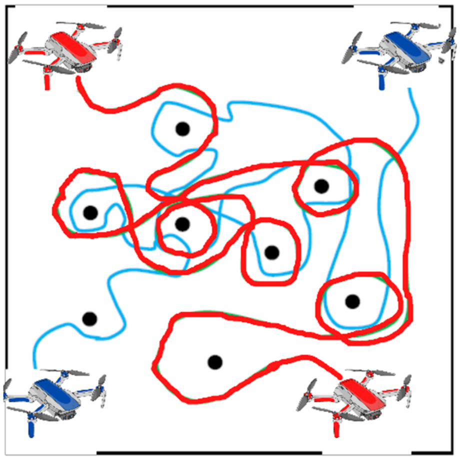

Figure 14. The trajectory of FANETs using ST models.

2.3.4. Enhanced Gauss Markov

The Enhanced Gauss Markov (EGM) mobility model is a realistic model that relies on the GM model and is dedicated exclusively to FANETs [63]. The uniqueness is that the UAV direction is computed slightly differently from the GM model because it uses direction deviation to limit the sharp turn and sudden stops. Furthermore, EGM includes a novel boundary avoidance mechanism, allowing soft changes and smooth trajectory at the boundaries, as shown in Figure 15. The following is how the EGM works. The node is given a random speed and direction at the start of the experiment. The speed is typically chosen randomly from a uniform distribution in the 30–60 m/s range, suitable for quadcopter UAVs. The angle is chosen randomly from a homogeneous range of 0°–90°. Several modern FANETs operations use EGM model [64,65].

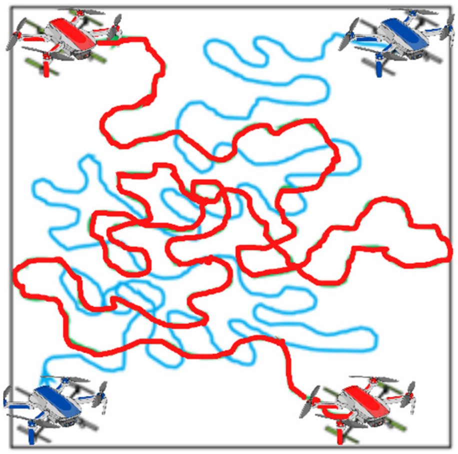

Figure 15. The trajectory of FANETs using EGM models.

2.4. Path Planned Mobility Models

In these path-planned models, a predetermined trajectory is generated ahead of time and stored into each UAV, forcing it to track without making random movements. The UAV could change random patterns or repeat the operation at the end of this predetermined trajectory.

2.4.1. Flight Plan

Flight Plan (FP) mobility model [66] is a path-planned model that defines a flight UAV plan in a special file for mobility. It is then used to make a time-dependent network topology map, as shown in Figure 16. Whenever the present flight plan and the original flight plan vary, the latter gets modified. Moreover, FP is commonly used for tactical mission and aerial transportation operations, where the whole flight trajectory is planned before starting a mission. It has been widely used in data collection from the sensor to UAVs [67]. Further, it can be adopted in semantic-aware aircraft trajectory prediction [68]. Figure 16 illustrates the approach.

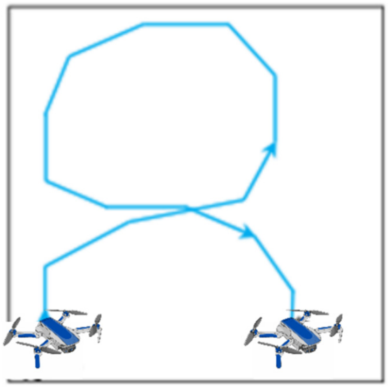

Figure 16. The trajectory of FANETs using FP models.

2.4.2. Semi Random Circular Movement

The Semi Random Circular Movement (SRCM) model is intended for UAVs that need to move along curved paths. It may be used to simulate UAVs flying around a specific central point to collect data [69]. After completing a full round, the UAV chooses a new circle at random and goes around the same predetermined center once more. Figure 17 depicts the movement of UAVs using SRCM. Further, the key benefit of SRCM is that it reduces the possibility of UAV collisions owing to the circular pattern of the motion. SRCM is widely adopted in search and rescue missions and has been implemented in a variety of applications such [70,71].

Figure 17. The trajectory of FANETs using SRCM models.

2.4.3. Paparazzi

The Paparazzi Model (PPRZM) is a probabilistic path-planned model that replicates Paparazzi UAVs' behavior inside the Paparazzi autopilot flight motion [72]. Further, it is a design based on a state machine that can perform five possible motions: Waypoint, Scan, Stay-At, Eight, and Oval. In the beginning, every UAV selects a starting position, movement type, and speed. After that, UAVS selects a random altitude that will be maintained during the experiment. PPRZM's varied UAV movement patterns are displayed in Figure 18. This model has been implemented in several FANETs applications, such as software-defined networking FANETs (SDN-FANETs) and a system to predict the UAV information [73]. In addition, this model is used in UAV video dissemination services [74].

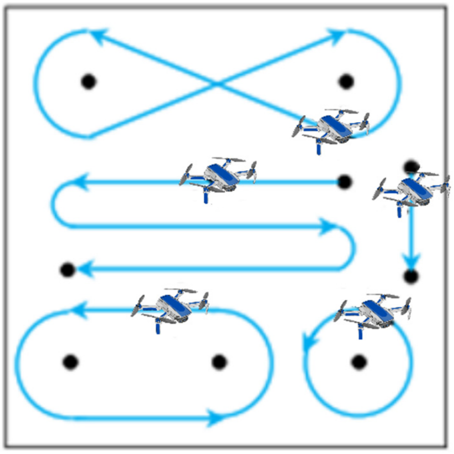

Figure 18. The trajectory of FANETs using PPRZM models.

2.5. Comparison of Existing Mobility Models for FANETs

A UAV's mobility is governed by several parameters, including path, flying altitude, UAV speed, direction, and atmospheric condition. These parameters are not considered in simple mobility models despite the level of random motion employed for each mobility model being one of the first aspects to consider. The curve of a UAV is then compared to an actual curve that is smooth and is represented by many basic mobility models as a general rapid change of direction. Then, there is the avoidance of connection, which is described as the distance between the UAVs. Finally, the deployment area and safety standards, such as safety distance, must be considered to avoid collision between UAVs. Table 2 summarizes these characteristics and all previously described FANETs mobility models.

Table 2. Comparison of FANETs mobility models.

Mobility Model	Reference	Categories	Randomness	Smooth Curves	Connectivity	Collision Avoidance	Deployment Area
RW	Ref. [36]	Random	√	×	×	×	2D
RWP	Ref. [39]	Random	√	×	×	×	2D
RD	Ref. [41]	Random	√	×	×	×	2D
MG	Ref. [43]	Random	√	×	×	×	2D
CLMN	Ref. [47]	Group	×	×	√	√	3D
ECR	Ref. [50]	Group	√	×	√	×	3D
NC	Ref. [53]	Group	√	×	√	×	3D
PRS	Ref. [55]	Group	×	×	√	√	3D
BSA	Ref. [56]	Time-Dependent	×	√	×	×	3D
GM	Ref. [57]	Time-Dependent	×	√	×	×	3D
ST	Ref. [60]	Time-Dependent	√	×	×	×	3D
EGM	Ref. [63]	Time-Dependent	×	√	×	×	3D
FP	Ref. [66]	Path-Planned	×	√	×	√	3D
SRCM	Ref. [69]	Path-Planned	√	√	×	√	2D
PPRZM	Ref. [72]	Path-Planned	×	√	×	×	2D

Remarks: √: supported, ×: Not supported.

3. Challenges for Routing Protocols in FANETs

The primary issues for routing protocols on FANETs are explained in this section, including high mobility, dynamic topology, low latency and QoS, remaining energy, and communication standards and various links. Every issue is briefly covered. Figure 19 depicts the main challenges for the FANETs routing protocols.

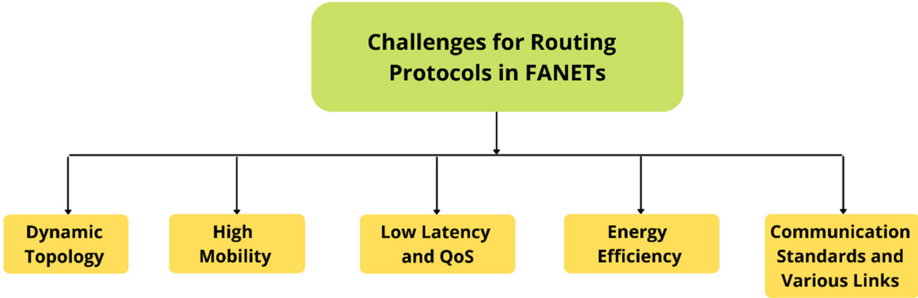

Figure 19. Challenges for FANETs routing protocol.

3.1. High Mobility

UAV nodes have greater mobility than that of MANETs and VANETs [75]. Every UAV node is extremely mobile, traveling at speeds ranging from as low as 30 to as high as 460 km per hour [76]. Mobility models in UAV networks are based on the application and depend on the type of UAV deployed in the field: multi-rotor, vertical take-off and landing (VTOL), or fixed-wing. The considered UAV type has an impact on the most suitable mobility model. The use of global path planning for UAVs is favored in some multi-UAV systems. On the other hand, multi-UAV systems operate independently, with no predetermined path. Mobility models such as the GM model, which allows UAVs to follow flexible trajectories, can be employed in search and rescue operations. In the GM model, UAV movement is dependent on previous directions and speed, which helps UAVs relay networks [77]. Due to its highly dynamic nature, node mobility is considered the greatest challenge in UAV routing.

3.2. High Dynamic Topology

Low link quality is an issue with FANETs due to the extremely high dynamic network topology caused by high mobility. As a result, link disconnections and network partitions frequently increase route discovery and maintenance and reduce routing performance [78]. Peer-to-peer connections are established to sustain coordination and collaboration between UAVs [79]. A multi-UAV Network is an ideal option for homogeneous and small-scale missions. Multi-cluster networks are required when particular UAVs must perform several missions.

3.3. Low Latency and Enhanced QoS

Due to the high speeds at which information must be transferred, search and rescue operations, surveillance, and disaster monitoring have a low-latency requirement. As a result, selecting the best routing protocol for minimizing latency and enhancing QoS in UAV networks is critical. As discussed in Khudayer et al. [80], route discovery and route maintenance must minimize latency. Priority schemes are a technique that can be utilized in UAV networks to control and minimize delay [81]. Distributed priority-based routing protocols can also be used to regulate the quality of service (QoS) for different types of messages [82,83]. Controlling packet collisions and traffic congestion effectively is also an important consideration for reducing latency in the network, such as FANETs.

3.4. Energy Efficiency

Battery-powered UAVs have limited energy to retransmit packets in the event of a route failure, and to execute routing tasks such as route discovery, updates, and maintenance. Furthermore, because of the relatively high distance between UAVs, UAV energy is normally utilized to support a long transmission range, which can quickly drain the limited battery capacity. As a consequence, UAVs consume a lot of energy [84]. UAVs must preserve energy to support lengthy flight times because energy availability influences route lifetime [85]. The number of UAVs required to meet network performance criteria, such as throughput and packet delivery ratio, is also considered to minimize energy consumption.

3.5. Communication Standards and Various Links

Multi-UAV networks can be used for most civilian and disaster-monitoring applications [86]. Different types of communication links may exist in multi-UAV systems, such as UAV-to-UAV, UAV-to-satellite, and UAV-to-ground. The IEEE 802.11 standard technology is commonly utilized in FANETs for ad hoc communication. Because it can manage larger bandwidth with fast data rates and long-range coverage, IEEE 802.11 can be utilized for UAV-to-ground communications. The IEEE 802.15.4 standard can be used for UAV-to-UAV communications with lower bandwidth requirements. IEEE 802.15.4 allows for a low-power, simple implementation with a lower data rate [87]. Moreover, TR 22.829 of the Third Generation Partnership Projects (3GPP), issued in 2019, identifies a number of UAV-enabled applications and use cases provided by 5G networks and the required communications and networking performance enhancements [88]. UAVs can communicate with each other ad hoc to avoid transmission range limits. For a variety of applications, this wireless network is utilized to send data between nodes in multi-hop communications.

4. Topology-Based Routing Protocols in FANETs

When it comes to network topology-based routing methods, the information from the nodes' links is utilized to distribute packets. Routing protocols use the IP addresses in the network to identify nodes that employ topology-based routing. The system's complexity and great mobility force regular topological changes. However, existing routing is unsuitable for highly dynamic FANETs since it was designed for MANET or VANET. Therefore, several researchers have tried to develop the classical routing protocol by adding extension features or modifying the control messages to adopt in FANETs. In fact, routing protocols in FANETs networks are extremely difficult to design. Furthermore, FANETs are uniquely different from MANETs, hence several of the MANET routing protocols are tailored to their specific characteristics. Proactive, Reactive, Hybrid, and Static are FANET's subcategories of topology-based routing protocols, as shown in Figure 20.

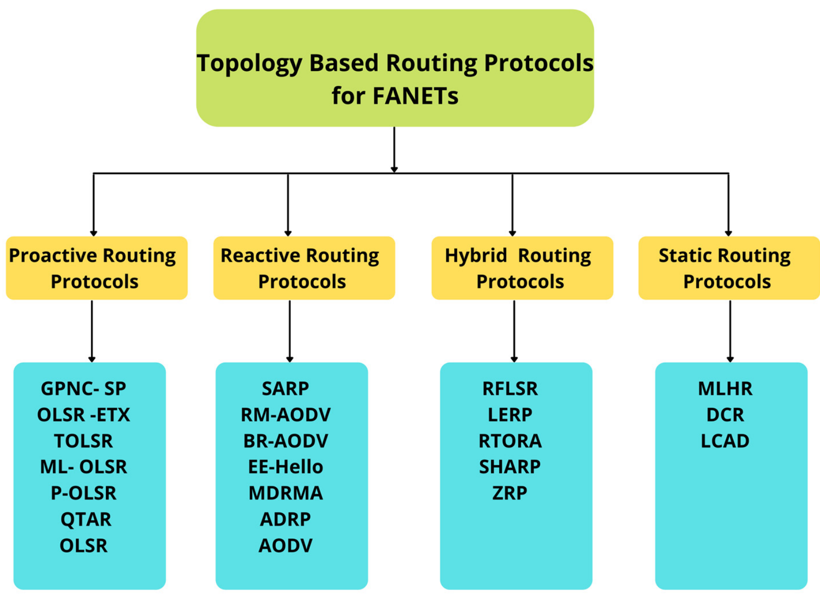

Figure 20. Categories of Topology-Based Routing Protocols for FANETs.

4.1. Proactive Routing Protocol

Proactive routing protocols maintain a routing table that contains all of the network's routing information. These routing tables are updated and shared between nodes periodically, and tables must be updated when the topology changes. The primary benefit of proactive routing protocols is that they always have the most up-to-date information. Routing messages must be transmitted between all communication nodes to maintain the routing tables. As a result, proactive routing algorithms precompute pathways to all network destinations in order for nodes to begin data delivery immediately, dramatically lowering delivery delay.

Grid Position No Centre Shortest path (GPNC–SP) is an unmanned aerial system shortest path routing algorithm. It replaces the original Euclidean distance with the logical grid distance to lessen the sensitivity of fast-moving nodes. By utilizing a perception and updating algorithm, this algorithm automatically computes and maintains the adjacency connection and topological structure, and utilizes the Dijkstra algorithm to find the shortest routing path. Additionally, a regional reconstruction technique (RSS) is used to optimize the routing path dynamically. Simultaneously, two metrics are employed to establish the optional scope of logical grid width, namely, the percentage of the effective communication area and the sensitivity to logical grid size. MATLAB was used to validate the protocol against the DSDV and DREAM routing protocols [89].

OLSR-ETX is a new implementation of the optimized link-state routing (OLSR) protocol that can adapt to quick dynamic topology changes and prevent communication interruptions. The crucially important concept is to leverage GPS information to determine when the link on the path should be expiring and choose the best relay node based on remaining energy. The NS-3 simulator performs the improved multimetric ETX (expected transmission count) simulation in OLSR. In terms of packet transmission, end-to-end delay, and overhead, the improved OLSR with expected transmission count (OLSR-ETX) outperforms the traditional OLSR [90].

TOLSR is a novel protocol that utilizes the trajectory of unmanned aerial vehicles as a known factor to improve optimum link-state routing (OLSR). To determine the optimal route for the system, Q-learning is used in this protocol. Additionally, a packet-forwarding system is detailed to tackle a typical issue encountered by UAVs: declining image quality. The simulation findings demonstrate considerable gains over OLSR and GPSR in a sparsely distributed environment, with the packet delivery ratio increasing by over 30% and the end-to-end delay decreasing by over 40 s. Several search and rescue simulation scenarios were implemented using MATLAB software [91].

The ML-OLSR protocol is a modified OLSR protocol that incorporates FANETs mobility and load awareness. In order to carry out the computations, two algorithms were installed in the protocol that used the GPS information of nodes. The first mobility-aware algorithm utilizes a statistical estimation of communication channels to calculate the stability degree of nodes. Thus, each surrounding node was assigned a weight, and then a reachability degree for the node was calculated. The second load-aware algorithm was able to identify nodes in the network by looking at the queued packets that were present at a node's interfaces and how much interference its surrounding links caused. QualNet's simulator was used to model and simulate the ML-OLSR protocol. In terms of packet delivery ratio and end-to-end delay, the ML-OLSR protocol performed better [92].

P-OLSR is an OLSR protocol for FANETSs that is predictive in nature. It facilitates effective routing in highly dynamic environments. The P-OLSR protocol makes routing decisions dynamically by utilizing the nodes' GPS information. To optimize routing decisions, the protocol calculates the expected transmission count (ETX) by comparing the speeds of two flying nodes. The addition of location information enhances the link quality extension by allowing for rapid analysis of the network's link breakage characteristic. Results were acquired using a MAC-layer emulator that incorporates a flight simulator to mimic flight conditions accurately. These numerical findings demonstrate that predictive-OLSR surpasses OLSR and BABEL in communication reliability, even under highly dynamic settings [93].

QTAR is a new Q-learning-based routing protocol for FANETs that enables efficient source–destination combinations in highly dynamic situations. By considering two-hop neighbor nodes in the routing decision, the QTAR protocol enhances the local view of the network topology. QTAR adaptively updates the routing decision based on the network situation using the Q-learning technique. GPS signals can be used to determine the location of UAV nodes in QTAR. The geographic routing strategy based on two hops enhances routing performance. According to simulation results, QTAR outperforms conventional routing protocols across a range of performance measures in various scenarios [94].

OSLR is a routing protocol that is widely used in ad hoc networks. The most critical factors affecting the performance of OLSR are contained within multipoint relay (MPR) nodes. The sender node's function is to select the MPR node, covering two-hop neighbors. Nodes in UAV networks frequently change their location and interconnection link. MPR is a critical feature in OLSR for reducing control messages. MPR nodes are a subset of nodes that are tasked with the responsibility of forwarding link-state updates. This optimization to a pure link-state routing protocol is advantageous in extremely dense network environments, where the MPR technique is optimal [95].

4.2. Reactive Routing Protocol

Routing protocols that react to the on-demand routing situation are known as reactive routing protocols. When two nodes communicate with one another, a route between them is stored. RRP's primary design purpose is to overcome proactive routing techniques' overhead problem. Only when a UAV wishes to establish contact is a route discovery process initiated, during which the greatest number of possible routing paths is examined, defined, and maintained. Due to the length of time required to find the route during the routing procedure, excessive latency may arise. The discussion that follows discusses available reactive routing protocols for FANETs.

The SARP protocol is a newly created reactive protocol that follows the Ant Colony Optimization meta-heuristic. It determines the next hop node based on the link's stable value, pheromone, and energy. The next hop for packet forwarding is selected using a stable value, link energy, and pheromone, resulting in an optimization of the route-finding process. The stable value is determined by calculating the internode distance between the present node and the next-hop nodes, and the node's transmission range. The pheromone deposition is accomplished using Forwarding ANT (FANT) and Backward ANT (BANT) messages, which serve as route request and response messages, respectively. A periodic broadcast of hello messages is used to gather information about adjacent nodes. SARP outperforms AODV in packet delivery percentage, throughput, and normalized routing load, as demonstrated by simulations using NS2 [96].

The IEEE 802.11s standard has proposed the RM-AODV protocol. When mesh protocols (MPs) are mobile and designed to operate at layer 2 using MAC addresses instead of Layer 3 addresses. RM-AODV is ideal as it alleviates the upper layers of the complexity of path determination, allowing them to see all UAVs as a single hop away. The protocol's path cost measure represents both the link's quality and the number of resources needed when a particular frame is transmitted over that link. Based on NS3-Evalvid simulations, the suggested protocol enhances the network performance by delivering improved latency, packet success rate, overhead cost, and the peak-signal-to-noise ratio of the received video [97].

BR-AODV is a protocol for unmanned aerial vehicles that are bioinspired in nature (UAVs). The protocol is modified and extends the AODV routing protocol to incorporate Boids of Reynolds, connectivity, and a route-maintenance mechanism that simulates the movement pattern of a flock of birds to show the mobility of UAVs in the air. The BR-AODV protocols follow three rules: separation, alignment, and cohesion to keep nodes connected in the network. Performance testing of BR-AODV showed that it outperforms AODV in terms of throughput, delay, and packet loss [98].

Using mission-related information such as the volume of the authorized airspace, number of UAVs, UAV transmission range, and UAV speed, the energy-efficient hello (EE-

Hello) is a new adaptive hello-interval method. EE-Hello defines a method for determining the distance traveled by a UAV before sending a hello message. Additionally, it defines a technique for determining the number of UAVs required to meet specified network requirements, such as packet delivery ratio or throughput, while consuming the least amount of energy possible. The results indicate that the proposed EE-Hello can save around 25% of the energy now consumed by suppressing unneeded hello messages without compromising network speed [99].

MDRMA is a new routing and power management protocol. MDRMA can be seen as a significant extension of the mobility-aware dual-phase AODV with adaptive hello messages. Specifically, in the MDRMA-Routing algorithm, routes are not established arbitrarily but instead are established based on the fulfillment of specific requirements that may be deduced from the affirmative responses to the following questions. The MDRM-Routing method ensures the establishment of stable routes with high-speed data transmission via wireless networks. MDRMA contributes effectively to network stability mitigation by generating fast and stable routes and reducing connection failures, as demonstrated by simulation findings [100].

ADRP is a novel FANETs adaptive density-based routing technology. ADRP is an upgraded AODV protocol that uses route freshness information to optimize its route-finding process. The primary purpose is to adaptively calculate forwarding probability in order to maximize forwarding efficiency in FANETs. ADRP dynamically adjusts a node's rebroadcasting probability to request packet routing based on the number of adjacent nodes. Indeed, it is more interesting to prioritize retransmissions made by nodes with fewer neighbor nodes. The simulation findings indicate that ADRP outperforms AODV in end-to-end delay, packet delivery percentage, routing load, normalized MAC load, and throughput [101].

AODV is a reactive routing protocol that operates on a hop-by-hop basis. It establishes the route between source and destination only when the source begins it and maintains it for as long as it desires. The source node broadcasts a route request (RREQ) packet to discover the destination. The number of hops necessary to reach the destination is contained in a route reply (RREP) packet. In the event of an invalid route, a route error packet (RERR) is issued to warn the source node of the link failure and to allow the source to restart the route discovery process. AODV automatically adapts the dynamic link-state, memory overhead, and network utilization [102].

4.3. Hybrid Routing Protocol

Hybrid protocols overcome the shortcomings of proactive and reactive procedures by combining their strengths. Indeed, proactive and reactive protocols both require significant overhead to maintain the entire network and a sufficient amount of time to discover and choose the optimum routes. As a traditional approach, hybrid protocols employ the concept of zones, deploying the proactive strategy only within the zones, hence minimizing overhead. In terms of inter-zone communication, the reactive technique is applied only amongst zone-specific nodes. Hybrid protocols are well suited for large-scale networks with several sub-network areas.

RFLSR is a proposed coordination strategy for maintaining the drones' topology and distributing recruiting requests to assist the drone in parasite killing. Two approaches have been proposed: one based on proactive topology management, such as LSRS, and another based on reactive topology management, such as RFS. The reactive strategy appears to be the most effective in terms of parasite-killing efficacy and the most scalable in terms of network bytes transferred. The two tactics were simulated in an ad hoc simulator specifically developed for this application domain, and a preliminary examination of the drone design's practicality for this purpose was conducted. This preliminary work enabled the development of a simulator with more realistic conditions for evaluating the drone network's performance [103].

LEPR is a novel hybrid routing protocol based on AODV that is aimed at FANETs. By utilizing the GPS location information of FANETs, a new link stability metric for LEPR is introduced. This new metric utilizes safety degree, link quality, and mobility prediction factors to account for the link's past, current, and future stability. LEPR calculates numerous robust link–disjoint pathways using this new metric throughout the route discovery procedure. Additionally, a semi-proactive route maintenance operation is launched when anticipating connection breakage. This preemptive method minimizes the number of broken paths and packet latency by identifying and switching to a more reliable path early. In both high- and low-mobility simulations, LEPR outperforms AODV and DSR in terms of delay, packet delivery ratio, and routing overhead [104].

TORA is a hybrid routing protocol that emulates the characteristics of a swarm network with unmanned aerial vehicles (UAVs). Based on TORA's link reversal failure, the RTORA protocol suggests employing the so-called reduced-overhead method and thereby resolves the problem caused by TORA's link reversal failure. In OPNET's simulation results, RTORA has a reduced control overhead and a better end-to-end delay performance than TORA in the anticipated hostile environment [105].

By dynamically adjusting the number of routing control packets shared proactively, SHARP often provides a trade-off between proactive and reactive routing. Proactive zones are formed around a group of UAVs based on the maximum distance at which control packets should be shared. When the destination UAV is not located in the proactive zone, the reactive technique is applied. SHARP enables each UAV node to regulate the routing layer's adaptation using a separate application-specific performance metric. UAVs in the same proactive zone take proactive measures to preserve paths. In SHARP, proactive zones operate as collectors, which means that once data packets reach a zone's UAV, they are accurately sent to the destination. Simulation results demonstrate that the SHARP protocols outperform both proactive and reactive protocols across a wide variety of network parameters [106].

ZRP, as the name implies, is based on the concept of zones. Each node has its zone. A zone is a collection of nodes. Intra-zone routing is a term that refers to routing within a zone that utilizes ZRP. Data communication can begin immediately if the source and destination are in the same zone. ZRP utilizes a route discovery technique for destinations outside the zone that takes advantage of the zones' local routing information, referred to as inter-zone routing [107].

4.4. Static Routing Protocol

The static routing table is suitable for networks with a consistent topology, but it is insufficient for FANETs. To communicate, each UAV's routing table is calculated and populated in advance of the flight and then saved in the UAV. It should be emphasized that routing tables cannot be changed, limiting UAVs to communicating with a small number of other UAVs or ground-based base stations. This routing protocol is well suited for nondynamic networks and is designed to be fault-tolerant. Static protocols are unable to function normally in the event of link failures, causing disruptions throughout the network.

MLHR is a statically routed protocol that was created to address the network's scalability issue. FANETs are arranged into clusters, each of which has a cluster-head (CH) that serves as the cluster's representative. Each CH has unique external and internal connections via UAVs with a direct communication range. This type of routing may be appropriate for FANETs if the mobility of UAVs is predefined in terms of swarms or a high number of UAVs are present in a large network. Hierarchical design is used to expand the operating area and size of the network [108].

DCR is a data-centric static and multicast routing protocol. This is possible when a data packet or message is requested by a group of UAVs and distributed reactively, such as in one-to-many transmissions. DCR is used in cluster-based FANETs to serve a variety of applications that distribute explicit data for a specific mission area. DCR is built on a publish–subscribe strategy that automatically connects data publishers and subscribers.

The publisher initiates data transmission, which is intercepted directly or indirectly by the intended UAVs. The publisher initiates the data broadcast, which is intercepted either indirectly or directly by the intended UAVs [109].

LCAD is a dedicated static routing mechanism for FANETs. Before UAVs take off, LCAD configures the navigation path on the ground. UAVs act as a link between a pair of source and destination ground stations by collecting, transporting, and transmitting data packets. If the UAVs carrying the data packets are not heading in the correct direction, other UAVs might take over and deliver the data packets. LCAD is also used in delay-tolerant networks (DTNs) and is occasionally used in search and rescue (SAR) applications. This approach is secure and has a high throughput. However, the method's primary disadvantage is that transmission delay may be significant due to the great distances involved [110].

5. Comparison of Topology Based Routing Protocol

This section comprehensively compares the key characteristics, routing approach, mobility models, simulation methodology, performance metrics, and application scenario of conventional and newer topology-based routing protocols. Table 3 identifies the major features of existing topology-based routing protocols, and Table 4 compares the characteristics of the different routing protocols.

Table 3. Main features of topology-based routing protocols.

Protocol Type	Protocol Name	Reference	Main Feature
Proactive	OLSR	Ref. [95]	MPRs technique and use link quality extension
	P-OLSR	Ref. [93]	Fast response to Network topology changes
	ML-OLSR	Ref. [92]	Reduce the time required for MPRs selection and path disconnections
	GPNC-SP	Ref. [89]	Reduce the overhead in the network
	OLSR-ETX	Ref. [90]	Support high-mobility networks
	TOLSR	Ref. [91]	Improve image quality during transmission in FANETs
	QTAR	Ref. [94]	Considers two-hop neighbor nodes while making routing decisions, broadening the local perspective of the network architecture.
Reactive	AODV	Ref. [102]	Utilize network bandwidth efficiently
	ADRP	Ref. [101]	Optimize messages of route discovery based on probability of adaptive forward
	RM-AODV	Ref. [97]	Suitable for video surveillance and can handle an increase in bandwidth
	BR-AODV	Ref. [98]	Suitable for surveillance mission and forest fire
	SARP	Ref. [96]	Reduce the rebroadcasting of control message of route request
	EE-Hello	Ref. [99]	Enhanced routing process by reducing the number of hello messages and reducing energy consumption for UAVs
	MDRMA	Ref. [100]	Provide a new routing mechanism by controlling the date rate with respect to the mobility of UAVs
Hybrid	ZRP	Ref. [107]	Enhance the efficiency of route query and reply for reactive nature
	SHARP	Ref. [106]	Reduce the number of zones to decrease the overhead
	RTORA	Ref. [105]	Support several routing techniques and loop-free
	LERP	Ref. [104]	Support breakages in low link
	RFLSR	Ref. [103]	Enhance energy efficiency based on link-state routing
Static	LCAD	Ref. [110]	Enhance routing security and achieve maximum throughput
	MLHR	Ref. [108]	Suitable for large FANETs
	DCR	Ref. [109]	Transmit data from one UAV to many UAVs in FANETs

Table 4. Comparison of topology-based routing protocols.

Protocol Type	Protocol Name	Year	Route Type	Mobility Model	Simulation Tool	Performance Metrics *	Application Scenario
Proactive	OLSR	2003	Dynamic	RWP	NS-2	RO	FANETs
	P-OLSR	2013	Dynamic	PPRZM	Test bed	DL	Relay, Open area coverage
	ML-OLSR	2014	Dynamic	RWP	QualNet	PD, ED	FANETs
	GPNC-SP	2018	Dynamic	GM	MATLAB	RO, LS	FANETs
	OLSR-ETX	2018	Dynamic	RWP	NS-3	ED, PD, RO	Ocean FANETs
	TOLSR	2020	Dynamic	PPRZM	MATLAB	ED, PD	Search and rescue
	QTAR	2021	Dynamic	GM	MATLAB	PD, ED, RO, EC	Monitoring applications.
Reactive	AODV	2003	On demand	RWP	NS-2	PD, ED	FANETs
	ADRP	2017	On demand	RWP	NS-2	PD, ED, NR, TH	FANETs
	RM-AODV	2017	On demand	MG	NS-3	ED, PD, RO, PS	Video Surveillance
	BR-AODV	2017	On demand	N/A	NS-2	GO, DR, ED	Surveillance
	SARP	2018	On demand	RWP	NS-2	PD, TH, NR,	FANETs
	EE-Hello	2019	On demand	GM	NS-3	PD, TH, RO, EC	Green UAVs
	MDRMA	2019	On demand	RWP	NS-3	ED, RO, PD,	FANETs
Hybrid	ZRP	2002	Hybrid	RWP	GloMoSim	ED	FANETs
	SHARP	2003	Hybrid	RWP	GloMoSim	PO, LR, DJ	FANETs
	RTORA	2013	Hybrid	RWP	OPNET	RO, ED	Swarm Network
	LERP	2017	Hybrid	RWP	NS-3	PD	FANETs
	RFLSR	2019	Hybrid	PPRZM	Others	EC, NK, TB	Agriculture
Static	MLHR	2000	Static	RWP	GloMoSim	RO	FANETs
	DCR	2005	Static	RWP	Others	ED	FANETs
	LCAD	2007	Static	FP	Test bed	PD, TH	FANETs

* Performance metrics, RO: routing overhead, DLR: datagram loss rate, PD: packet delivery ratio, ED: end-to-end delay, LS: link stability, EC: energy consumption, NR: normalized routing load, TH: throughput, PS: peak-signal-to-noise-ratio, GO: goodput, DR: drop rate, LR: loss rate, DJ: delay jitter, NK: number of killed parasites, TB: transmitted bytes.

Table 3 lists the unique creative characteristics of each of the 22 studied topology-based routing protocols for FANETs. According to our findings, proactive and reactive routing techniques perform better in highly dynamic FANETs than other protocols do. Furthermore, mostly under the monitoring application, hybrid protocols are appropriate for large-scale FANETs.

6. Open Issues and Future Research Directions

Exciting and promising research areas and issues are addressed and discussed in this section. Since UAV routing protocols are still in the early stages of development, the network dynamic nature and link disconnect, delay and QoS, simulation tool, energy consumption, coordination and collaboration, and flying in 3D space are the main challenges for developing a topology-based routing protocol for UAV networks. The enhancement of routing scalability, the elimination of complexity in topology-based routing, the reduction of routing latency, energy-efficient routing, improved routing security, and equitable load distribution across nodes are the difficulties that need to be addressed. This section summarizes six complex challenges that will be useful to academics and engineers while deciding on a routing protocol or designing a new one for FANETs.

6.1. Network Dynamicity and Link Failures

The network is very dynamic, and the topology often changes because of the rapid speed of UAVs in FANETs. Due to the UAVs' shifting locations, linkages can be formed and broken often, resulting in intermittent connections. This destabilizes the communication network, having a negative influence on routing efficiency and performance. The node density is modest in most applications, and the network split can last for a long time. Because of failure or energy fatigue, UAVs can exit and rejoin the network at any time. Topological changes are also caused by mission updates on the fly and environmental barriers such as mountains, temperature variations, and geographic uncertainty. Networks with broken connections make routing extra difficult in UAV networks. Developing routing protocols would become a complex undertaking due to this complexity. Further research investigation can be done to address these challenges. For instance, diversifying and selecting relay nodes to establish the significance of the cooperative diversity technique with bio-inspired computing can be used in routing protocols to reduce the link breakages [111].

6.2. Various Quality of Service (QoS) Requirements

Various kinds of services, such as streaming media and real-time communications, have their own set of QoS requirements, such as jitter and end-to-end delay, as well as high bandwidth. Voice over Internet Protocol (VoIP) and video streaming and services, for example, necessitate a constrained low end-to-end delay and jitter and delay [112]. On the other hand, data transfer applications require high levels of reliability and packet delivery ratio [113].

Fault tolerance is necessary for certain applications for higher QoS, which may be implemented using topology-based routing protocols. As a result, meeting QoS requirements in UAV routing is yet another unsolved problem. The modeling findings of UAVs in high-speed movements reveal increased latency, which is one of the major disadvantages. As a result, the delay threshold is regarded as a difficult problem. Furthermore, a significant issue in routing that supports mobility is that the protocol must be prepared to accommodate the overhead when nodes are mobile and the network topology changes often. The majority of routing protocols are constrained by delays and costs. Nevertheless, other criteria such as route mobility, QoS metrics, stability, connection quality, and security technology and access control may be considered while designing an efficient routing protocol. Further study might be done to construct adaptive FANETs to improve QoS using various solutions such as the K-means clustering method [114].

6.3. Simulation Tools

Different network simulation tools and mobility models are utilized to assess the existing and proposed routing protocols for FANETs. Partially, OMNET++, OPNET, MATLAB, NS-2, and NS-3 are used to evaluate the performance of the majority of current routing systems. Nevertheless, most simulators, including NS-3, do not enable 3D mobility models or mimic any specific channels for UAV communication. Only 2D random mobility models are supported throughout most simulators, not preset control-based mobility. Consequently, the vast majority of them fail to provide realistic or reasonable outcomes. To develop topology-based routing protocols in FANETs, significant improvements for a new simulator that supports more realistic mobility models and satisfies multi-UAV requirements are crucial to gain realistic and reasonable output results. Recently, several researchers developed a new FANETs simulator AVENS, a novel FANETs simulator with code generation for UAVS [115]. The Opportunistic Network Environment (ONE) Simulator enables real-time simulation and emulation. Further, it can be used to assess the performance of FANET with DTN while accounting for a range of characteristics such as buffer storage, mobility patterns, and routing algorithms [116].

6.4. Energy Consumption

Most commercial UAV applications rely on batteries for routing, data transmission, data processing, UAV mobility, and payload applications. As a result, the flight length of UAVs for specific missions is restricted, and UAVs often leave and rejoin a network for energy replenishment, which has a direct influence on the network's communication performance. As a result, while developing routing protocols for FANETs, the energy level of the UAVs must be taken into account to keep the UAV connections stable. However, only a tiny percentage of contemporary FANETs routing systems take energy into account as a routing measure. As a result, energy-conscious routing and energy preservation require more research work. For instance, in FANTs, a cluster-based routing protocol is employed to decrease energy consumption [117]. Furthermore, optimizing the performance of standard protocols such as LEACH can be adopted in FANETs to provide energy efficiency routing protocols [118].

6.5. Coordination and Collaboration between UAVs

Collaboration and coordination among UAVs are necessary for preventing collisions between many UAVs. Cooperation and coordination amongst UAVs are critical for enhancing routing efficiency in large-scale UAV networks and multi-UAV missions. For improved UAV communication, dynamic route planning is necessary. In dense deployment, decreasing the end-to-end latency between UAVs is still a key research area. Furthermore, a swarm of UAVs and satellites can generate a satellite–UAV network (CSUN) to provide wide area coverage for 6G and IoT applications [119]. Recently, 6G mobile communication technology has been proposed to provide communication for a swarm of UAVs to perform a specific mission [120].

6.6. 3D Scenarios

The majority of UAV routings are often placed on a 2D surface, even though UAVs move in 3D space. The major issue in 3D UAV routing is managing the mobility of the UAV nodes. To improve routing efficiency in multi-UAV networks, UAVs must communicate in 3D space while considering critical characteristics. Design swarms of UAVs in 3D UAV networks lead to a plethora of novel application scenarios. For instance, research focuses on developing a 3D mobility model with a smooth trajectory in FANETs [121].

7. Conclusions

In FANETs, the routing mechanism is crucial for cooperative and collaborative network functions. Several routing protocols for FANETs have been developed in several studies over the past few years. Diverse FANETs mobility models, routing protocol design challenges, network topologies, and different types of communication links have been reviewed and presented. In addition, several existing and innovative topology-based routing protocols for FANETs have been thoroughly reviewed and compared. The 22 topology-based routing protocols have been categorized into four categories: proactive, reactive, hybrid, and static routing protocols. The routing protocols were then compared in terms of characteristics, various routing mechanisms, mobility models, routing performance measurements/parameters, simulation tools involved in the development, and application scenarios. Based on our comparison, each routing protocol has its own advantages/disadvantages, and suitability to specific applications. Further, a low density of UAV nodes must be considered when developing topology-based routing protocols in FANETs. Moreover, three-dimensional space, time-dependent and path-planned mobility models are widely adopted for various FANETs application scenarios. Finally, opportunities and challenges related to FANET deployment were highlighted in this article.

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