A Comprehensive Review on State of the Art Improvements in Routing Frameworks for Flying Ad-Hoc Networks

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***Abstract*—Improving routing frameworks to extend the lifetime of Unmanned Aerial Vehicles (UAVs) and improve the Quality of Service (QoS) of its nodes are crucial in Flying Ad-hoc Networks (FANETs). To realize these goals, there have been ongoing research that has led to a plethora of routing protocols to improve the QoS offered. However, several challenges in relation to autonomous and random deployment of nodes, energy constraints of the routing protocols, and flight path selection, among others, are still existing concerns. This paper presents a systematic review of state of the art improvements on routing protocols in FANETs in order to identify gaps and present likely areas for future research. Since this paper focuses on the routing protocols for FANETs, this work excluded grey literature and considered 22 peer-reviewed journal publications on FANETs routing frameworks that are not older than 5 years and were primarily obtained from 3 databases. To identify the gaps in the selected literature and present likely research directions, this paper presents wireless ad-hoc networks and compare the various network types. The mobility models utilized in the routing protocols are discussed, giving preference to those that were utilized in the literature reviewed in this paper. This is done to aid researchers assess the quality of studies. Furthermore, the routing metrics and frameworks are discussed, while the frequency of performance measures, mobility models, and simulators utilized in the literature reviewed in this paper are also highlighted to enable researchers, engineers, and policymakers save time and resources in making informed evidence-based decisions on the metrics and frameworks discussed. The work is concluded after delineating a number of open challenges with likely research directions for future works.**

Keywords—flying ad-hoc networks, mobility models, routing, routing frameworks, unmanned aerial vehicle, wireless ad-hoc networks

I. INTRODUCTION

The ever-expanding field of Flying Ad-hoc Networks (FANETs) continues to be a focal point of intrigue and innovation in a digital age distinguished by interesting breakthroughs in communication. These networks, which use the sky as their communication medium, go beyond the constraints of conventional land-based communication systems to present an area where land-based technology meets the open expanse of the sky. However, the open expanse, which aids mobility comes with a plethora of challenge that results in routing overhead [1], failing routing performance [2], energy concerns [3], among other, that impacts the Quality of Service (QoS) of FANETs [2, 4]. As such, analyzing and building on the existing routing frameworks or developing new frameworks to improve FANETs' operability and efficacy becomes imperative as flying nodes traverse this dynamic environment.

FANETs are a subset of wireless ad-hoc networks that share the same mobility characteristics as Mobile Ad-hoc Networks (MANETs) and Vehicular Ad-Hoc networks (VANETs) [5]. This branch of its subset utilizes flying nodes, which in this case are usually called Unmanned Aerial Vehicles (UAVs) to either communicate information directly with a Base Station (BS) or use a dynamic mesh of connected nodes to transmit information within other nodes in the network until the information reaches the BS [1]. Additionally, UAVs are now often used in a variety of applications thanks to the development of automation and radio technology in recent years. Some of these applications include field rescue operations, surveillance, cargo transport, industrial monitoring, and communication relay [4]. Multiple UAVs work together to create FANETs, with at least one UAV linking to a satellite or ground station. FANETs demonstrate the potential to carry out complex and adaptive tasks at lower costs and more efficiency even in hostile circumstances. Their numerous uses include improving communication services, where a FANET can act as an aerial base station for cellular network customers [6].

By offloading computational duties when Internet of Things (IoT) devices reach their processing capacity, FANETs can play a crucial role in enabling edge computing. This is essential to avoiding significant response latency, especially in cases involving vehicular networks, where the FANET helps through compute offloading.

Additionally, as the sixth-generation mobile communication system (6G) develops with the advent of the era of ubiquitous connection, the need for superior communication links with increased precision becomes clear. To establish communication awareness through resource allocation and route planning, UAVs can be smoothly integrated with intelligent computers [1].

Part of the inspiration for this systematic review was drawn from the work of [2]. However, the goal of this work is to carry out a systematic review of routing protocols in FANETs in order to identify gaps and present likely areas for future research. As such, this paper utilises state of the art literature to discuss the progress in the routing frameworks for FANETs. In the process, certain changes were observed, which this work delineated in order to aid researchers, engineers, and policymakers in further modifications and possible development of present and/or future routing frameworks in FANETs. Delineated in the following are the contributions:

1. Classification of state of the art routing frameworks, the performance measurements utilized, the mobility models employed, and the simulator or emulator used.

2. An analysis of the mobility models, performance metrics, and simulation tools. This helps in identifying the increase in the usage of NS 3 simulator rather than MATLAB as identified by [2].

For the planning of this review paper, the goal was to consider papers not older than five years when reviewing the routing frameworks. Within this timeline, it was observed at the time of writing this paper that there were limited surveys that included SANETs in the comparison of Ad-hoc wireless networks. As such, we could only consult three recent papers within the timeline considered (that is, from 2018 - 2023) that included SANETs when discussing the variations between FANETs, MANETs, and VANETs. The primary database considered for this work was MDPI. Although, databases like Wiley and Elsevier were considered. However, for the IEEE papers that were considered, most of the papers from its database were not considered in the review of routing frameworks since the timeline of literature used at the time of writing were in most instance older than than the timeline considered for this review.

A. Recent Reviews on FANET Routing

Over the years, there have been several developments in routing frameworks to improve the QoS in FANETs. The evolution of these developments has been captured in several review literature under considerations such as mobility models, design considerations, simulators or emulators, and performance measures among others. Delineated hereunder are recent works that capture the development proposed by researchers.

The work of [2] presented an extensive investigation of routing frameworks for UAVs, which began with the evolution of FANET routing frameworks. Their features, techniques, benefits and limitations were delineated. In continuation, the routing frameworks discussed in the study were categorized based on their core techniques and compared to delineate the strengths and weaknesses of the techniques. Furthermore, the performance metrics used to weigh the performance of existing routing frameworks were presented. This was followed by an analysis of the metrics, tools, mobility modes and the purpose of the simulation. The work additionally discussed open issues identified and concluded with possible directions that needed to be addressed to further improve the QoS for FANETs.

The work of [7] carried out a survey on FANET to increase research interest on the subject of 3D movement and mobility of UAVs. As such, the paper began with the need for FANETs and their unique characteristics. This was used as a yardstick to make a comparison with other ad-hoc networks. The work additionally discussed the requirements for bandwidth, mobility models, taxonomy of FANET attributes, objectives, challenges, routing metrics, and performance measures, and concluded with open issues that needed to be addressed to enhance QoS in FANETs.

The work of [8] presented a review on the communications perspective of FANETs. The work discussed key enabling technologies and compared these wireless technologies. Furthermore, the applications were presented alongside the challenges. And conclusions were made.

The work of [9] presented insights into the categorization and mechanisms of UAVs in FANETs. To this end, the authors discussed the FANET architecture, the issues with mobility in FANET and the pros and cons to be considered in selecting an appropriate mobility model. Additionally, routing techniques were examined. The work concluded with a discussion on open issues and possible research directions to improve FANETs.

The work of [10] presented a review on wireless ad-hoc networks. The work gave an overview of MANET, VANET, SANET, and FANET. The characteristics of the four networks were compared. Although the mobility of UAVs in FANETs was discussed, the work did not discuss the models. The concluding part of the review highlighted possible directions to identify deployments in wireless ad-hoc networks.

The work of [11] discussed four families of wireless ad-hoc networks. The focus of the discussion centred on the definition, characteristics, classifications, development, and applications of wireless ad-hoc networks. The paper concluded with potential future directions.

The work of [12] presented an extensive study in reinforcement learning in FANETs. The authors wrote the paper to educate and increase interest in the application of RL in FANETs. In light of the aim, the work introduced the fundamentals of deep learning reinforcement learning, which was followed by a discussion on the fundamentals of FANET. Following the latter were the applications of RL in FANET. Then the work discussed the open issues on the application of RL in routing frameworks in FANETs.

The work of [13] discussed topology-based routing frameworks and mobility models. The paper presented the potential of FANETs in several UAV applications. Additionally, the work presented diverse mobility models and

the challenges faced by the routing frameworks in FANET. The taxonomy of routing frameworks in FANETs is discussed alongside a comparison of some routing frameworks proposed under the routing framework. Furthermore, open issues and future directions were discussed.

The work of [5] discussed the application of reinforcement learning on routing frameworks. In this regard, the fundamentals of RL were concisely discussed followed by an overview of FANETs. In continuation, the work proposed classifications of RL-based routing algorithms in FANET, which was used in investigating RL-based routing frameworks. The authors delineated challenges identified and concluded the review.

The work of [14] presented a review of position-aware routing frameworks in FANET that was based on Q-Learning alongside the pros and cons in FANETs. Additionally, key performance features of the routing protocol were compared. Furthermore, open issues and research challenges, as well as potential research directions in FANETs are discussed.

The work of [15] presented a systematic review on bio-inspired routing frameworks for FANETs. The bio-inspired routing methods were discussed. Additionally, the work presented a taxonomy and analyzed several mobility models that captured various bio-inspired routing frameworks for FANET. A statistical analysis of simulators and the performance metrics were presented. Furthermore, the challenges identified were discussed and the work concluded by discussing future research directions.

Table 1 presents a summary of recent survey papers on FANET. The key areas considered to delineate the similarities and peculiarities of the works are as follows:

COMPARISON OF STATE OF THE ART SURVEYS ON FANET ROUTING

Authors	**Parameters**							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**
[7]	Y	Y	Y	Y	Y	N	Y	Y
[8]	Y	N	Y	Y	Y	N	Y	Y
[9]	N	N	Y	N	N	N	N	N
[10]	Y	Y	Y	Y	Y	N	Y	Y
[11]	Y	N	N	N	N	Y	Y	N
[12]	Y	N	Y	N	Y	Y	N	Y
[13]	Y	Y	N	N	N	Y	Y	N
[14]	Y	Y	Y	N	Y	N	Y	Y
[15]	Y	N	Y	Y	Y	N	Y	N
[5]	Y	Y	Y	Y	Y	N	N	Y
[16]	Y	Y	Y	Y	Y	N	Y	Y
Our paper	Y	Y	Y	Y	Y	Y	Y	Y

Where P1: Routing Frameworks, P2: Simulation Environments, P3: Open Issues; P4: Performance Measures, P5: Mobility Models, P6: Comparison with Existing Ad-Hoc Networks including SANET, P7: Future Research Directions, P8: Taxonomy of Routing Frameworks.

Fig. 1 presents a taxonomy of recent routing frameworks considered in this research.

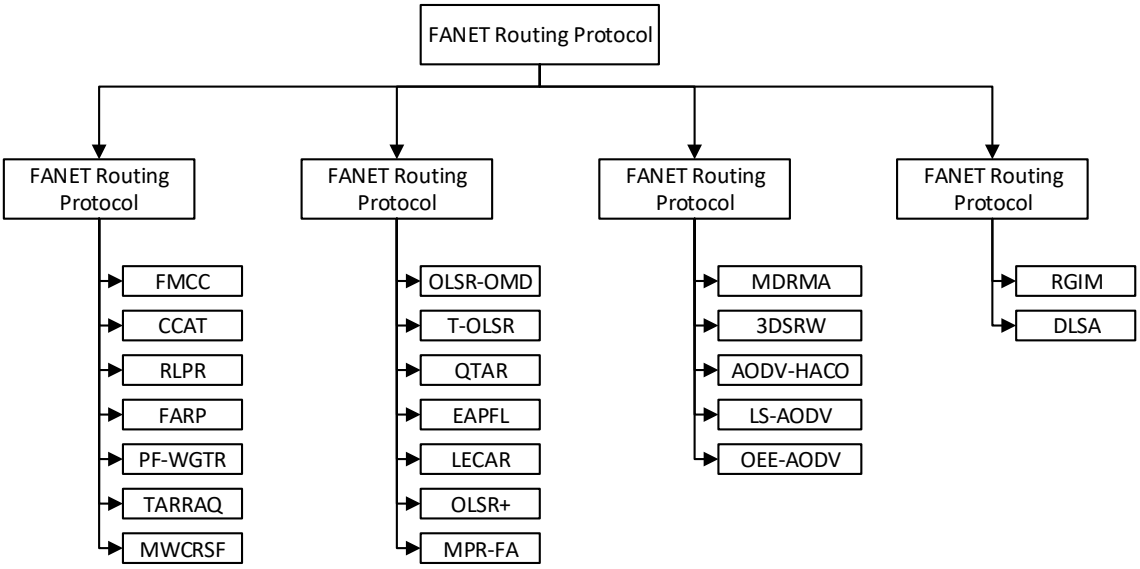

Fig. 1. Taxonomy of Routing Frameworks

B. *Organization of the Paper*

The rest of this paper is organized as follows: section II discusses the wireless ad-hoc network, with its characteristics, and presents a comparison of the ad-hoc networks considered in this study. Section III discusses the mobility models in FANETs. Although, preference is given to the models that are present in the papers reviewed for this work. Section IV discusses the routing metrics in FANET, while the routing frameworks are discussed in Section V. Research work implemented under the routing frameworks is reviewed. Section VI presents a result of the frequencies of performance measures, mobility models, and simulators adopted in recent literature to improve routing in FANETs. Section VII presents open issues with likely directions for future research. Section VIII concludes the work.

II. WIRELESS AD-HOC NETWORKS

Wireless Ad-hoc networks are decentralized communication systems in which nodes or sensors communicate to one another directly rather than through a centralized infrastructure like routers or access points. These networks allow data to be transmitted from one node to another, allowing for the formation of dynamic and self-organizing network topologies. Each node in the network functions as both a transmitter and a relay station. Since they lack a fixed network infrastructure and are flexible and mobile, wireless Ad-hoc networks are well-suited for a wide range of scenarios and applications [16].

Ad-hoc wireless networks include the following key characteristics:

Decentralization: Wireless Ad-hoc networks lack fixed infrastructure and centralized management. The network topology can vary dynamically, and nodes communicate with one another autonomously.

Self-Organization: Ad-hoc network topologies can quickly change as a result of node mobility or other circumstances, which is known as dynamic topology. Routing and management protocols must be effective since nodes can enter or leave the network at any time.

Dynamic Topology: The Ad-hoc network topologies can quickly change as a result of node mobility this is generally known as dynamic topology. Routing and management protocols must be effective since nodes can enter or leave the network at any time.

Versatility: Wireless Ad-hoc networks are used in a variety of fields, such as vehicle networks, disaster recovery, environmental monitoring, and military communications. In situations where conventional infrastructure is unworkable or unavailable, they can be deployed.

Wireless Ad-hoc network types that are frequently used include Mobile Ad-hoc Networks (MANETs), Vehicular Ad-hoc Networks (VANETs), Flying Ad-hoc Networks (FANETs), and Sea Ad-hoc Networks (SANETs), each of which is designed for a particular application environment and has its own characteristics and concerns:

A. *Flying Ad-hoc Networks (FANETs)*

Micro Aerial Vehicles (MAV) or Unmanned Aerial Vehicles (UAVs) that operate in a three-dimensional airspace are grouped together in dynamic networks called FANETs. FANET is a unique class of MANET that is comparable to VANET. In relation to mobility, FANETs shares the same characteristics of mobility as MANETs and VANETs [10]. As a result, these networks are frequently used for operations like surveillance, data collecting, and communication relay in situations where conventional infrastructure is impracticable or non-existent. Some common issues of FANETs include managing mobility in 3D space, maintaining dependable communication in unpredictable circumstances, reducing the energy consumption of UAVs, and following airspace laws.

B. *Mobile Ad-hoc Networks (MANETs)*

MANETs do not rely on a fixed infrastructure for communication between nodes. These networks are flexible and self-organizing, which makes them appropriate for uses like military operations and disaster relief [17]. Nodes and devices in a MANET can move independently and freely in any direction. The infrastructure (base station) required by MANET prevents each network node from serving as a router. The routers can move randomly and arrange themselves as they see fit. Consequently, the wireless network architecture may change often and in an unpredictable manner [12].

C. Vehicular Ad-hoc Networks (VANETs)

VANETs are a subset of MANETs and are made up of vehicles that have onboard communication systems that permit inter-vehicle communication. The dynamic infrastructure of VANETs is designed to improve traffic control, provide infotainment services, etc. to improve vehicle-to-vehicle communications, vehicle-to-road communications, and in-vehicle communications [12]. Changing network topologies quickly as a result of vehicle mobility characterizes VANETs. Designing reliable and effective routing protocols, assuring scalability in large-scale deployments, managing network congestion, and putting in place reliable security procedures, particularly in applications involving vehicle safety, are challenges in VANETs.

D. Sea-Ad-hoc Networks (SANETs)

The main goal of SANET is to improve aquatic connection by linking diverse aquatic nodes, which could be boats, ships, submarines, vessels, and Unmanned Surface Vehicles (USV). The node density, which tends to be moderate because these nodes are distributed over oceans, affects the specific distribution of nodes inside a given location. Although at a slower rate than the dynamic topology changes found in VANETs and FANETs, increased USV mobility inside a SANET can lead to frequent changes in network topology [11].

E. Variations in FANETs, MANETs, VANETs, and SANETs

Ad-hoc networks are generally self-configuring, decentralized wireless networks that don't require a centralized infrastructure like routers or access points for communication between devices or nodes. These networks' adaptability, dynamic topology, and capacity to quickly form in a range of situations are what make them unique. This paper discusses four subsets of Ad-hoc networks, which are FANET, MANET, VANET, and SANET. A unique class of MANET called FANET is comparable to VANET. In other words, FANET shares the same characteristics of mobility as MANET and VANET [11]. The frequency bands used by Ad-hoc networks differ by region and application. For FANETs, MANETs, VANETs, and SANETs, common bands such as the ISM bands (such as 2.4 GHz and 5.8 GHz) are used for short-range communication in drones and UAVs, 5.9 GHz DSRC bands are used for safety-critical VANET applications, and sub-1 GHz bands are used for long-range communication in SANETs that are used for a variety of sensor applications [12].

The range of computational capability includes more resource-constrained nodes like sensors in SANETs to highly capable devices like UAVs and vehicles in FANETs and VANETs, respectively. Depending on the particular network type and application requirements, this diversity enables these networks to support a wide range of applications, with nodes carrying out duties that range from straightforward data forwarding and routing to complicated data processing, analysis, and decision-making [9, 11]. The nodes' limited energy capacity is a result of both their mobility and battery-powered design. Depending on the particular network type and application, these restrictions might vary. UAVs in FANETs and mobile devices in MANETs frequently struggle with low battery capacity, necessitating effective energy management to increase operational periods. In VANETs, vehicles frequently rely on their internal power systems, which can be limited during lengthy use. In order to extend node lifespan in SANETs, which are made up of energy-sensitive sensors, power management must be carefully considered [10, 15].

Regarding LoS communication, they are typically available in FANET and SANET, while they are occasionally available in VANET, and unavailable in most cases in MANETs. Ad-hoc networks like FANETs, MANETs, VANETs, and SANETs frequently use positioning technologies like GPS, Differential GPS, Assisted GPS, and Inertial Measurement Unit (IMU) because they offer a variety of levels of accuracy and contribute to localization. These technologies range from standard GPS, which has meter-level accuracy, to DGPS, which achieves sub-meter to centimeter-level precision, AGPS, which increases speed, and IMU, which provides highly accurate measurements subject to drift over time [18]. Node density significantly affects the performance of FANETs, MANETs, VANETs, and SANETs. While low node density yields sparser network structures with decreased connectivity and coverage, it can also result in increased interference [7]. Depending on the particular application and environment, node speeds in Ad-hoc networks might vary significantly. For pedestrian nodes in VANETs or sensor nodes in SANETs, these speeds can be as low as a few kilometers per hour, or as high as 150 kilometers per hour. Depending on their objective, UAVs in FANETs can move at various speeds, ranging from relatively moderate rates for surveillance and data collection to fast speeds for applications requiring rapid response or delivery. Likewise, the node speeds of devices in MANET also vary greatly, from stationary nodes to devices moving at walking rates or faster [11].

Radio propagation is through air and water for FANETs and SANET, respectively, while both MANET and VANET are through land. All the Ad-hoc networks considered in this paper utilize adaptive, proactive, reactive, and hybrid routing frameworks [7]. Security at all levels is considerably high. To improve connectivity and communication, IEEE wireless technologies are widely used in FANETs, MANETs, VANETs, and SANETs. For example, IEEE 802.11a/b/g/n for wireless LANs is frequently used in MANETs and VANETs, while SANETs may make use of low-power wireless frameworks like IEEE 802.15.4. Depending on the objectives of the operation, FANETs frequently use a variety of wireless technologies, sometimes even proprietary or unique frameworks developed specifically for UAV communication. Within Ad-hoc network contexts, these IEEE standards and wireless technologies enable dependable and standardized communication [10]. Table 2 shows a comparison between FANETs, MANETs, VANETs, and SANETs.

VARIATIONS IN FANETS, MANETS, VANETS, AND SANETS

Criteria	Wireless Ad-hoc Networks			
	FANETs	**MANETs**	**VANETs**	**SANETs**
Frequency band	2.4GHz/5.9GHz	2.4GHz-5GHz	5.9GHz	5GHz
Computatonal Power	High	Low	High	High
Energy limitation	Depends on UAV	High	Low	Low
Line of Sight	Typically available	Unavailable in most circumstance	Occasionally available	Typically available
Localization	AGPS, DGPS, GPS, and IMU	GPS	AGPS, DGPS, and GPS	DPS, GPS
Mobility models	Regular and random	Random	Regular	Random
Node density	Low	Low	High	Medium
Node mobility	Very high	Low	High	Medium
Node speed	Up to 500km/h	Up to 25km/h	Up to 150km/h	Up to 130km/h
Node type	UAVs, helicopters, aircraft	Laptops, smartphones, tablets	Cars, buses, trucks, etc.	Ships, boats, vessels
Raio propagation	Air	Land	Land	Water
Routing protocol	Adaptive, proactive, reactive, hybrid	Adaptive, proactive, reactive, hybrid	Adaptive, proactive, reactive, hybrid	Adaptive, proactive, reactive, hybrid
Security	High levels of data integrity, dependabilty, and privacy	High levels of data integrity, dependabilty, and privacy	High levels of data integrity, dependabilty, and privacy	High levels of data integrity, dependabilty, and privacy
Topology change	Stationary, slow, and fast	Dynamic, unpredictable	Linear movement, but progressive	Stationary, slow-moving
Update topology	Often	Not often	Often	Not often
Wireless technology	IEEE 802.11a/b/g/ac/s/n/p	IEEE 802.11a/b/g/n. IEEE 802.16	IEEE 802.11p	IEEE 802.11ah

III. MOBILITY MODELS IN FANETS

FANETs' mobility model, which establishes how UAVs move and interact in three-dimensional (3D) airspace, serves as a crucial foundational element for these dynamic aerial networks. As such, understanding and predicting the UAVs' mobility patterns in FANETs becomes crucial in order to maximize their potential and provide effective operation. Discussed hereunder a number of mobility models. The selected models discussed in this work are identified in the literature reviewed in section V.

A. Random Way Pont

The random waypoint model functions by independently selecting each node's destination and speed at random. The node then continues at the specified speed until it reaches the selected destination. When the node reaches its target, it pauses for an arbitrary amount of time before resuming the process and choosing a new speed and destination at random [10]. Although the random walk mobility model was not utilized in the literature reviewed for the routing frameworks in this paper, it is seen to have some similarities to the random waypoint model. However, it differs from the random waypoint model by introducing random changes in node speed and direction at set intervals or after a set distance. Compared to the more deterministic random waypoint model, the random walk model is more unpredictable due to this dynamic feature [13].

Node mobility in FANETs is crucial in determining how well the network performs. The random waypoint model is a good option for FANETs since it can simulate a variety of mobility patterns and is therefore appropriate for a wide range of applications. Its intrinsic simplicity in use and comprehension further increases its appeal. Some of the works that adopt the RWP mobility model are identified in section V.

B. Gauss Markov

The Gauss-Markov mobility model, a stochastic framework, depicts the movement of a node in a manner akin to a random walk, and its movement is influenced by both the mean velocity and the variance. The variance denotes the degree of randomness in the motion of a node, whereas the mean velocity denotes the node's average speed. This model's ability to mimic the erratic and unpredictable trajectories of UAVs makes it useful in the field of FANETs. Its widespread application in FANET research is a result of its simplicity of use and adaptation to different settings [19]. Due to its simplicity, adaptability, realistic representation of UAV motion, and effectiveness in evaluating various protocols and applications, the Gauss-Markov mobility model has been extensively utilized in FANET research. However, it has several drawbacks, such as failing to take environmental impediments and UAV interactions into account. Some of the works that adopt the Gauss-Markov mobility model are identified in section V.

C. Chain Mobiity

This chain mobility model was proposed by [20]. The proposed model was created by combining the Gauss-Markov and Random waypoint mobility models. The reason the authors combined both models was due to the widespread acceptance and use of the Random Waypoint and Gauss-Markov mobility models in existing research for simulating routing protocols in FANETs.

D. Reference Point Mobility

Due to the inherent variability of speeds and directions in FANETs, the Reference Point Mobility Model (RPM) simplifies the movement of FANET nodes by assuming that all nodes move at the same speed and in the same direction. As a result, real-world node mobility cannot be reliably simulated by RPM. Aside from barring random or clustered movement patterns, RPM's low flexibility restricts its applicability to a small number of mobility circumstances. Additionally, it is computationally inefficient because it must determine the distances between every pair of nodes, which is difficult in bigger networks, which makes it unfavourable for FANET research.

E. Random Direction

Random direction, also known as random mobility, uses an approach akin to determining the direction of movement of a node as the random waypoint model. However, the main difference is the requirement for the node to stop on the perimeter of a predefined zone [7]. Consequently, the endpoint must be on the boundary of the fixed space, not within the space itself [21].

F. 3D Smooth Random Walk

The work of [22] extended the 2D random walk model into 3D space to better represent UAV movements. In the initial 2D model, the nodes start randomly in a 2D region and then move at randomly chosen speeds and directions until the node ends or reaches the boundary of the simulation. In 3D, the authors considered the three-dimensional velocity direction, relatively lower vertical velocity after UAV stabilization, and the need to smooth randomly generated trajectories for UAV manoeuvrability. The authors claimed that the 3D random walk model solves the problems of 3D velocity representation, boundary processing, and trajectory smoothing by assuming that UAV nodes act as particles, ignoring external factors such as weather conditions and UAV collisions.

For further review of other mobility models in FANETs, the works of [9] and [13] can be considered.

IV. Routing Metrics in FANET

Generally, there are five routing metrics that are utilized in FANETs to determine the part that would be travelled by a UAV.

1) Mobility Metrics: Under this metric, there are a number of performance factors that are used to weigh the weigh its impact on FANETs. These factors are the angle of arrival, distance, and speed. The impact of these metrics impact routing stability and Improving QoS and routing efficiency. Since nodes whose speed or Angle of Arrival (AoA) are likely the same are chosen to be a part of a route to extend the lifetime of the route.

2) Link expiration time: Similar to improving the QoS and routing efficiency in mobility metric to extend the route lifetime, this factor identifies that the increase in the link expiration time between two UAVs conversely lengthens the lifetime of the route. This metric aids in the realization of two objectives, namely, improving the stability of the route and improving QoS and routing efficiency. Considering the realization of the said objectives, the stability of the node can be improved by selecting nodes with a larger number of neighbouring nodes and lengthened link expiration time. Selecting nodes with the above-mentioned factors as part of the route improves the stability of the route. Secondly, to ensure seamless network operations, a new route can be set up before a link expires.

3) Geographical location: There is a considerable distance between nodes in FANET so nodes with higher and closer neighbouring nodes are considered for routing. However, the probability that the number of hops within the route increases, which likely leaves the signal exposed to interference, attenuation, Noise, and propagation delay, which can compromise the signal and reduce the network performance. Generally, this metric brings about the realization of two objectives, namely, improving the stability of the route and improving the QoS and routing efficiency. The features of selected nodes, which require them to have a higher number of neighbouring nodes that are closer to each other can lengthen the lifetime of the route and conversely reduce the amount of updating that is necessary for the routes, as well as minimize the process of finding routes and maintaining them.

4) Residual Energy: This metric is like the triumvirate of the aforementioned objectives of FANET as it aids in realizing the objectives of routing in FANET. This achievement reduces the inefficient resource utilization in finding routes and maintaining them. Thereby, minimizing disconnections in the link and reducing the energy consumed [7].

5) Node Identity: This metric like the one aforesaid also achieves all three objectives of FANET. In this metric, the node ID is crucial. Fundamentally, the ID of the nodes is required for

the selection of intermediate nodes as they are required for the intended nodes to receive the signal and transmit the signal to the destination equipment. Although node selection might be random, the routing path largely depends on the characteristics of the routes.

A. Performance Measures

The performance and effectiveness of data communication among UAVs in FANET are largely impacted by routing. To analyse the efficacy of routing frameworks in FANET, a variety of performance measures are utilised. Discussed hereunder are the measures taken to weigh the performance these performances:

1) *Higher throughput:* This measure is closely related to QoS. In instances in which the QoS is high, the throughput and packet delivery rate both increase. On the other hand, end-to-end delay and packets that are sensitive to delay are reduced..
2) *Lengthened network lifetime:* The UAVs' energy consumption is a significant factor in this measurement. The lifespan of the FANET network can be increased by lowering the amount of energy that the UAVs use.
3) *Intra-cluster and inter-cluster communication:* The number of clusters in FANET is inversely proportional to the cluster size. As such, a few number of clusters reduces the probability of intra-cluster communication. The goal is to have a larger number of neighbouring UAVs to reduce the resources in finding routes for hop-to-hop routing, which can lengthen the lifetime of the route. Within a cluster, the group of UAVs that make up the members of the cluster are known as Cluster Members (CM) and the UAV that leads the cluster is the Cluster Head (CH).
4) *Route setup success rate:* Although the characteristics of routes in FANET vary, success in setting up a route is crucial. The capability of the UAV to establish a route between the source UAV and the destination UAV is vital when the route setup success rate increases.

V. Routing Framework

The overseeing framework that guides the transmission of signals transmitted from a source UAV to a destination UAV generally consists of three steps. Discussed in the following are these steps.

In the first step, the neighbouring UAVs and route discoveries enable the UAVs (i) to periodically update its set of neighbouring UAVs. This is achieved by periodically broadcasting control messages to identify changes in the network topology. And (ii) to exchange routing messages along potential routes between the source UAV and the destination UAV. From the source UAV, a Route Request (RREQ) is broadcasted to the destination UAV to obtain routing metrics such as the geographical location and the UAV ID. In response to the RREQ, the destination UAV uses the route it received the RREQ request to transmit a Route Reply (RREP) to the source UAV.

As highlighted in the first step, the selection of a route enables the UAVs to utilize the routing metrics discussed in sub-section 4 to select routes in the second step.

In the third step, the dynamic nature of FANET, which can complicate routes between source and destination UAVs can be managed by periodic route maintenance as this helps the UAVs to reestablish routes.

A. Categories of Routing Frameworks in FANETs

As discussed in the work of [7], there are four main categories of routing frameworks in FANET. These categories are dependent on the selection of routes earlier discussed. Delineated hereunder are the frameworks of the routing schemes:

1) Adaptive: This routing scheme uses the knowledge obtained from the present topology of the network to find the optimal route between the source and destination UAVs. Due to the dynamic nature of what could eventually become the current state of the network, the scheme adapts by learning, selecting, and dynamically changing its route from the information garnered from the present condition of the network. It then uses this information gathered to update its route. The following discussion delineates recent literature that discusses adaptive routing frameworks for FANET.

The work of [23] proposed a Fuzzy Markov Chain Cluster (FMCC) in FANET. The model addresses the problem of neighbouring route maintenance to prevent routing crises and reduces packet loss during transmission. The simulation tool adopted was MATLAB. Though the work was not based on routing protocol design, the solution proffered by the authors was compared against existing frameworks such as AODV and EIPBP, while considering the cluster lifetime, throughput, as well as cluster formation, Packet Delivery Ratio (PDR), and End-to-End (E2E) delay to weigh its QoS in FANETs.

The work of [24] proposed a Connectivity-based Copy Adaptive Transmit (CCAT) Routing Algorithm for FANETs. In this work, measurements of network connectivity were utilized by CCAT to determine how to forward data packets. The Random WayPoint (RWP) model was used to generate the UAV movements. CCAT controlled how many copies of a packet to send in a network by examining network connections and utilizing a prediction value from the UAVs. This method determined forwarding decisions in consideration of both network interruptions brought on by rapid node movement. Additionally, the performance of the protocol was compared against existing frameworks like PRCP, PROPHET, and EPIDEMIC, while considering metrics like control packet overhead, search success rate, network lifetime, and E2E delay. The authors used Java to program the simulation environment.

The work of [25] proposed a Reliable Link-adaptive Position-based Routing (RLPR) protocol in FANET. For this protocol, a variety of performance indicators such as control packet overhead, search success rate, and network lifetime were taken into account to decrease unwanted control messages and achieve high connectivity levels in order to increase the trustworthiness of communication in FANET. An RWP mobility model was adopted to model the mobility of the UAV

and the performance of the protocol was considered existing frameworks such as AODV and RARP which was simulated using NS 2.35.

The work of [26] utilized an Intelligent and Hello Dessemination model based on reinforcement learning algorithms referred to as AI-Hello. This approach suppressed unneeded RREQs and took into account the UAV's features and performance in high-mobility situations. The performance of the proposed protocol was compared against variations of AODV and OLSR and was validated using PDR, E2E delay, constant bit rate, network overhead, and energy consumption. Additionally, a Gauss-Markov 3D model was used for the mobility of the UAVs, while the overall performance of the metrics considered for this protocol was simulated using NS-3.

The work of [21] proposed a Predicted Future Weight-based Routing (PF-WGTR) scheme for FANETs. Using this scheme, a weight-based routing method for FANETs that chooses a reliable routing path based on the UAV's present and future values of guaranteed parameters was based on projected future values. The suggested routing technique assigned a weight to each UAV in the network by forecasting its future. Based on the anticipated future weight of each UAV, the communicating UAV in a network could establish a reliable channel that lasts for a very long time. The performance of the proposed protocol was compared against FSQOS and QLF-MOR and validated using metrics such as energy consumption, delay, routing overhead, network throughput, and PDR.

The work of [27] proposed a Fuzzy Adaptive Routing Protocol (FARP) in FANETs. The model initially sent and received numerous RREQs and RREPs to find potential paths before determining the best route. The protocol then chooses the best path for delivering data packets after the best route is found. The work considered a RWP mobility model. Additionally, the delay, PDR, throughput, and routing overhead were considered as performance metrics and their performance was simulated using NS 3.

The work of [28] presented a Topology-Aware Resilient Routing strategy based on Adaptive Q-learning (TARRAQ) to achieve a high packet delivery ratio with a low delay, the model was designed to adapt to geographic variances and make routing decisions with minimal overhead. The performance of the proposed protocol was compared against GPSR-EE-Hello, MPVR, and QTAR. This was validated using PDR, E2E delay, energy consumption, and routing overhead. The simulation was implemented in a MATLAB environment.

The work of [29] proposed a Mobility-based Weighted Cluster Routing Scheme (MWCRSF) in order to eliminate unused control messages in the network and assist in locating effective routes, the model made use of the Number of clusters, cluster construction time, PDR, cluster lifetime, E2E delay, energy consumption, throughput, routing overhead, network lifetime as performance measures to weigh the impact of proposed scheme against existing schemes such as K-means, SOCS, MLSC, GWO, and DCM.

From the literature reviewed, it's been observed that the optimal route established using the proposed schemes under the adaptive routing framework in FANET adds to the efforts to mitigate network congestion and the disconnections created in the link. This in turn improves the performance of the network as data packets are sent and received by the source and destination UAVs, respectively. While this is an advantage of the adaptive scheme, the need for continuous learning to establish the optimal route increases computational complexity.

Table 3 shows a summary of recent literature that utilized the adaptive routing framework.

SUMMARY OF RECENT REVIEWS ON ADAPTIVE ROUTING FRAMEWORKS IN FANETS

Authors	Routing Protocol	Performance measures	Mobility model	Simulator	Work Done
[23]	FMCC	End-to-end (E2E) Delay, throughput, Cluster formation, Cluster lifetime, PDR	Reference point	MATLAB	The model solves neighbouring route maintenance problems to prevent routing crises and reduces packet loss during transmission.
[24]	CCAT	PDR, delay, hop count, overhead	Random Way Point (RWP)	Java	CCAT used the measurements from network connections to determine how to forward data packets. The forwarding utility value to manage the number of copies of packets also depended on the transmitted prediction of the UAV.
[25]	RLPR	Control Packet overhead, search success rate, network lifetime, E2E delay	RWP	N 2.35	The protocol decreased unwanted control messages and achieved high connectivity levels to increase the trustworthiness of communication in FANET.
[26]	AODV (AI-Hello)	PDR, E2E Delay, throughput, network overhead, energy consumption	Gauss-Markov 3D	NS 3	The protocol suppressed unneeded RREQs and took into account the UAV's features and performance in high-mobility situations.
[27]	FARP	Delay, PDR, throughput, routing overhead	RWP	NS 3	The protocol first forwards and receives numerous RREQs and RREPs to find potential paths before determining the best route. Then it chooses the best path for delivering data packets after the best route is found.

Authors	Routing Protocol	Performance measures	Mobility model	Simulator	Work Done
[21]	PF-WGTR	Energy consumption, delay, routing overhead, network throughput, PDR	Random direction	NS 2	The protocol chooses a reliable routing path based on the UAV's present and future values of guaranteed parameters and is based on projected future values. Based on the anticipated future weight of each node, the communicating nodes in a network can establish a reliable channel that lasts for a very long time.
[28]	TARRAQ	PDR, E2E delay, energy consumption, routing overhead	RWP	MATLAB	To achieve a high packet delivery ratio with a low delay, the model was designed to adapt to geographic variances and make routing decisions with minimal overhead.
[29]	MWCRSF	Number of clusters, cluster construction time, PDR, cluster lifetime, E2E delay, energy consumption, throughput, routing overhead, network lifetime		MATLAB	In order to eliminate unused control messages in the network and assist in locating effective routes, the model makes use of a variety of performance measures.

2) Proactive: Routing strategies that are proactive keep track of all network routes. Every node in the network registers its route information with every other node. These frameworks maintain the most recent pathways for each node in the network by routinely exchanging and storing control data between the nodes involved. They are arranged according to the techniques they use, such as prediction-based and heuristic, as well as their objectives to address the demands and issues associated with FANET routing. [15]. Delineated hereunder are recent proactive frameworks proposed in the literature for FANET:

The work of [30] introduced an improved Optimized Link State Routing Protocol (OLSR-PMD) for UAV networks. This was proposed to mitigate the challenges of routing path failures and packet losses due to UAV mobility. The developed protocol employed mobility and delay predictions. A mobility prediction model based on the Kalman filter algorithm selected the stable multi-point Relay UAVs to enhance route stability. Additionally, a cross-layer queuing prediction model was used to balance traffic load and mitigate E2E delay. The algorithm for the proposed OLSR-PMD protocol outperformed existing DSDV and OLSR frameworks in terms of PDR and E2E delay.

The work of [31] presented a Trajectory Optimized Link State Routing (T-OLSR). The work applied Q-learning to find the system's ideal path. Additionally, a packet-forwarding system was described to address a common problem with UAVs such as deteriorating image quality. The performance measures considered to validate the work were E2E delay and PDR.

The work of [32] proposed an Energy-Aware and Predictive Fuzzy Logic-Based (EAPFL) Routing Scheme in Flying Ad-hoc Networks (FANETs). In order to find paths to the desired destination, AODV-based routing in the network can result in flooding of routing messages, which can cause a broadcast storm. This paper addresses the issues of failing communication routes and flooding of routing messages in the network. The first problem is caused by the high mobility of nodes in the network, which increases PLR and delays the data transmission process in the network. The first was to design stable paths during the route discovery process, and the second was to identify and quickly correct any paths that have reached the failure threshold. To stop the broadcast storm, the authors enhanced the AODV routing protocol and restricted the nodes that broadcast routing messages. In the suggested routing strategy, the authors took into account a number of factors, such as network quality, node stability, and UAV energy, to build stable routes and boost PDR. In order to extend the network lifetime, they also aimed to balance the energy used by flying nodes in our system.

The work of [19] presented the difficulties in developing efficient routing algorithms for Flying Ad-hoc Networks (FANETs) because of their dynamic topology, limited UAV energy, and three-dimensional node mobility. For highly dynamic FANETs, the current topology-based and one-hop neighbor-based routing techniques were considered to be insufficient. As such, the authors came up with Q-learning-based Topology-Aware Routing (QTAR), a novel routing protocol, to solve this problem. By taking into account two-hop neighbour nodes, QTAR improved routing decisions by enlarging the local perspective of the network topology. Based on the state of the network, the Q-learning technique provides adaptive routing decisions. Results from simulations show that QTAR performs better than the existing QGeo and GPSR routing frameworks in a variety of performance metrics across diverse circumstances.

The work of [33] discusses the difficulties of power-intensive unmanned aerial aircraft (UAVs) in broad areas routing in an energy-efficient manner. The work presented a Location Estimation-based Congestion-Aware Routing (LECAR) for Ad-hoc networks. The delivery of packets is improved by conventional Delay-Tolerant Network (DTN) routing algorithms but suffers from congestion and high energy consumption. This is lessened by the proposed LECAR, which makes routing decisions by estimating destination location using mobility patterns and taking into account both distance and surrounding UAV buffer occupancy. Simulations show that LECAR is capable of delivering packets at high rates, using little energy, and sending out few transmissions and copies of packets.

In order to enhance OLSR for FANETs, the work of [34] suggested a Fuzzy Logic-based routing method dubbed OLSR+.

The four key aspects of OLSR+ include evaluating the link lifespan between UAVs, choosing MPRs with a fuzzy mechanism, improving network topology discovery by changing the TC message style, and computing the routing table taking route energy and lifetime into account. The work compared the proposed OLSR+ against G-OLSR and OLSR. This was simulated using NS3. In comparison to G-OLSR and OLSR, the results show that OLSR+ reduced delay, improved packet delivery rate, throughput, and energy efficiency, and had a little bit more routing overhead.

The work of [5] introduced an energy-aware routing method using the Firefly algorithm for FANETs. The goal of the work was to improve FANET performance through the optimization of Hello and TC message formats. The introduction of a novel connection quality calculation technique, the application of the firefly algorithm for MPR node selection, and the generation of routing tables that took into account both energy and connection quality variables were considered. The proposed algorithm was compared against G-OLSR and the legacy OLSR algorithm, while considering performance measures such as E2E delay, routing overhead, PDR, throughput, and energy consumption.

Generally, the benefit of the proactive routing protocol observed from the papers reviewed is that packets can be transmitted right away without any initial delay caused by route establishment. There are, however, two drawbacks. Due to the highly dynamic nature of the network topology, where link disconnections and network partitions are frequent occurrences, nodes are required to communicate with one another often in order to construct, update, and maintain routes in the routing table. As a result, routing overhead is substantial and bandwidth usage is ineffective. As a result, packets are sent through less-than-optimal paths because routes in the routing table might not be sensitive to the dynamic nature of the network architecture [7]. In light of this, proactive routing may only be used for FANET after a sizable update. Table 4 presents a summary of proactive routing frameworks considered in FANETs.

SUMMARY OF RECENT REVIEWS ON PROACTIVE ROUTING FRAMEWORKS IN FANETS

Authors	Routing Protocol	Performance measures	Mobility model	Simulator	Work Done
[30]	OSLR-PMD	E2E Delay, PDR	RWP	NS 3	In this protocol, the OLSR based on the Prediction of Mobility and Delay (OLSR-PMD) used GPS positioning to predict the mobility of nodes. Additionally, the application of the Kalman filter on the position and velocity of nodes enhanced the proactive nature of the protocol. The proactive extension of the protocol is linked to the OLSR protocol.
[31]	T-OLSR	PDR, E2E delay		MATLAB	In this protocol, Q-learning was applied to find the system's ideal path. Additionally, a packet-forwarding system was described to address a common problem with UAVs: deteriorating image quality.
[32]	QTAR	PDR, E2E delay, routing overhead, energy consumption, network lifetime	3D Gauss-Markov	MATLAB	The QTAR protocol enriches the local perspective of the network architecture by taking into account two-hop neighbour nodes in the routing decision. QTAR uses the Q-learning technique to adjust the routing decision based on the network situation. UAV nodes in QTAR can be found using GPS signals to pinpoint their location. The two-hop geographic routing approach improves routing performance.
[33]	EAPFL	E2E delay, PDR, route stability, energy consumption	Gauss-Markov 3D	NS 2.35	In order to find paths to the desired destination, AODV-based routing in the network can result in flooding of routing messages, which can cause a broadcast storm. This paper addresses the issues of failing communication routes and flooding of routing messages in the network.
[34]	LECAR	PDR, Hop count, number of copies per packet, number of transmissions per packet, delay per packet, overhead, energy consumption	RWP	NS 3	The proposed LECAR reduces the high energy consumption and congestion rate using the traditional DTN by estimating destination location using mobility patterns and accounting for both distance and nearby UAV buffer occupancy while making routing selections. Simulations demonstrated that LECAR can send out few transmissions and copies of packets while delivering packets at fast rates, utilizing little energy.
[35]	OLSR+	Transmission delay, routing overhead, PDR, throughput, Energy consumption	Gauss-Markov 3D	NS 3	The authors proposed a Fuzzy Logic-based routing strategy known as OLSR+ to improve OLSR for FANETs. The four main components of OLSR+ are: assessing the link lifetime between UAVs; selecting MPRs with a fuzzy mechanism; improving network topology discovery by altering the TC message style; and computing the routing table while taking route energy and lifetime into consideration. In the study, the suggested OLSR+ was evaluated against G-OLSR and OLSR.

Authors	Routing Protocol	Performance measures	Mobility model	Simulator	Work Done
[5]	MPR-FA	E2E delay, routing overhead, PDR, throughput, energy consumption	RWP	NS 3	The OLSR method served as a model for the suggested algorithm. By enhancing Hello and TC message forms, introducing a novel connection quality calculation method, using the Firefly algorithm to choose MPR nodes, and creating routing tables that account for both energy and connection quality variables, it boosts FANET's performance.

3) Reactive: The Reactive frameworks use on-demand network discovery techniques upon the arrival of data packets to mitigate the bandwidth resources expended during the network discovery process of the proactive protocol. As such, the process does not need to store routing information in a routing table [21], which makes them bandwidth-efficient [7]. Delineated hereunder are recent reactive routing frameworks proposed in the literature for FANET:

The work of [35] proposed a Multi Data Rate Mobility Aware (MDRMA) protocol. MDRMA represents a significant advance over the mobility-aware dual-phase AODV with adaptive hello messages. Instead of being constructed at random, routes are generated in the MDRMA-Routing algorithm explicitly based on the fulfilment of specific requirements that may be inferred from the affirmative responses to the following questions. The MDRMA technique ensures the creation of dependable routes with quick data transfer across wireless networks.

The work of [22] focused on a three-dimensional mobility model to increase the accuracy of representing UAV movements in a defined environment. A 3D Smooth Random Walk (3DSRW) mobility model was adopted to mimic the mobility of UAVs. Simulations were conducted using the AODV routing frameworks to assess the PDR, E2E delay, and average throughput differences between 2D and 3D environments. The review also evaluates the performance of other routing frameworks such as DSDV, OLSR, and GPSR in addition to AODV in the 3DSRW developed 3D environment. The performance of the routing frameworks was validated using the aforementioned performance metrics.

The work of [36] presented a Hybrid ANT Colony Optimization (HACO) Routing Algorithm, which combines path accumulation and multi-path routing properties. An evaluation of the proposed AODV-HACO protocol using simulations in the OMNet++ Simulator showed that it performed path accumulation and multi-path routing for FANETs 6.56% better than the standard AODV protocol.

The work of [37] focused on the necessity for secure and reliable routing frameworks for unmanned systems, especially in light of newly developed nano drones. In order to improve the AODV protocol for FANETs, it suggested a unique routing protocol named "Lightweight Secure AODV (LS-AODV)". The LS-AODV protocol uses the Chaskey-12-based Message Authentication Codes (MACs) and the Trivium stream cipher to provide control packets with confidentiality, authenticity, and integrity. LS-AODV is compared to benchmark frameworks (AODV and OLSR) in terms of network performance and security advantages through simulations using the NS-3 network simulator. The findings demonstrate LS-AODV's enhanced performance over the OLSR protocol, parity with AODV in typical conditions, and superiority in thwarting black-hole attacks in FANETs.

The work of [38] attempted to increase routing effectiveness and fend off black hole attacks in FANETs. This is achieved using the Eagle Optimized Energy-Efficient Ad-hoc On-Demand Distance Vector (OEE-AODV) protocol is a proposal that focuses on safe, efficient routing while taking into account variables like trust, priority, latency, energy, and the prevention of black hole attacks. The protocol is divided into two phases: creating the best routes with reliable nodes and boosting security with RREP packets. OEE-AODV outperforms AODV and AODV-V2 frameworks in terms of performance assessment thanks to its high data transmission rates, throughput, and energy efficiency.

The benefit is that it solves the high routing overhead problem associated with proactive routing. In particular, it lowers the computational cost associated with maintaining and re-establishing routes on a periodic basis, improving bandwidth consumption. It also reduces the periodic exchange of routing messages across nodes. The initial delay experienced when establishing routes is the drawback of the routing protocol. Table 5 presents a summary of reactive routing frameworks considered in FANETs.

SUMMARY OF RECENT REVIEWS ON REACTIVE ROUTING FRAMEWORKS IN FANETS

Authors	Routing Protocol	Performance measures	Mobility model	Simulator	Work Done
[35]	MDRMA	E2E delay, PDR, routing overhead	RWP	NS 3.26	MDRMA with adaptive hello messages is a considerable improvement. The MDRMA-Routing algorithm creates routes based on specific needs deduced from positive responses to essential questions, providing dependable, quick data transport across wireless networks.

Authors	Routing Protocol	Performance measures	Mobility model	Simulator	Work Done
[22]	3DSRW	PDR, E2E delay, average throughput,	3D Smooth Random Walk	NS 2.35	It was underlined how accurate 3D mobility modelling for UAVs in FANETs was important. A performance evaluation of several routing frameworks was done when introducing the 3DSRW mobility model.
[36]	AODV-HACO	E2E delay, network throughput, PDR, packets lost percentage, routing overhead		OMNet++	To provide path accumulation and multi-path routing, the HACO Algorithm was introduced to enhance the AODV routing protocol for UAV FANETs.
[37]	LS-AODV	PDR, E2E delay, routing overhead, average network delay, network jitter	RWP	NS 3	The proposed LS-AODV is a safe routing protocol for unmanned systems using nano drones. With Trivium encryption and Chaskey-12 MACs for confidentiality and integrity, LS-AODV improves AODV. According to simulations, LS-AODV performs better than OLSR and is more effective against black-hole attacks in FANETs.
[38]	OEE-AODV	Throughput, E2E delay, packet success rate, pause time, energy consumption		NS 3	The authors examined issues with FANETs backed by UAVs. They focused on improving routing and fending off black hole attacks. In contrast to AODV and AODV-V2, the proposed OEE-AODV protocol promotes optimal and secure routing using trusted nodes, achieving high data delivery speeds, throughput, and energy conservation.

4) Hybrid: Hybrid routing frameworks were proposed to address the issues of control message bandwidth consumption, poor proactive protocol dynamism, and reactive protocol long route search delays. These hybrid frameworks are especially well suited for big networks since they operate by segmenting the network into zones or sub-networks. As a result, a reactive routing protocol is utilized for communication between zones while a proactive routing protocol runs within each zone. The most often used hybrid solution is the Zone Routing Protocol (ZRP). The network is divided into clusters of nodes by ZRP, where each cluster's maximum separation distance is predetermined. A proactive routing protocol is used within the clusters to direct nodes to a subset that is shared by both zones when they are in separate zones. Delineated hereunder are recent hybrid routing frameworks proposed in the literature for FANET:

Kaur et al. in [20] used mobility models to investigate how to improve QoS performance in FANET routing frameworks. The work suggested the use of the Random Gauss Integrated Model (RGIM), a combination of the Random Waypoint and Gauss-Markov models, to evaluate the AODV, DSR, and DSDV frameworks. In various circumstances, the RGIM simulates enhanced QoS performance characteristics for these routing frameworks, including delay, Packet Delivery Ratio (PDR), jitter, and throughput.

The work of [39] proposed a hybrid routing strategy Delay and Link Stability Aware (DLSA) protocol to address the issue of link stability. Additionally, the DLSA protocol was developed with the aim of enhancing PDR and decreasing E2E Delay in FANETs. The DLSA protocol enabled the collaboration of data forwarding and increased connection stability, which was achieved by combining elements of Distributed Priority Tree-based Routing and connection Stability Estimation-based Routing. In terms of E2E Delay, PDR, Network Lifetime, and Transmission Loss measures, simulation results demonstrate DLSA's higher performance in comparison to existing methods.

Table 6 presents a summary of hybrid routing frameworks considered in FANETs.

SUMMARY OF RECENT REVIEWS ON HYBRID ROUTING FRAMEWORKS IN FANETS

Authors	Routing Protocol	Performance measures	Mobility model	Simulator	Work Done
[20]	RDIM	E2E delay, PDR, Throughput, jitter	RWP, Gauss-Markov	NS 2	The primary goal of RGIM was to enhance the QoS performance of FANET routing frameworks, which was achieved by combining mobility models. The hybrid model was used to evaluate the effect on the AODV, DSR, and DSDV frameworks.
[39]	DLSA	E2E delay, PDR, Network lifetime, transmission loss		MATLAB	The DLSA protocol combines Connection Stability Estimation-based Routing and Distributed Priority Tree-based Routing. DLSA increases connection stability and collaboration in data forwarding.

Table 7 delineates the performance measures adopted by several researchers to validate the performance of different routing approaches

COMPARATIVE ANALYSIS OF FANET ROUTING FRAMEWORKS

Routing Frameworks	**Routing Approaches**				**Performance Measures**															
	A	P	R	H	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**	**R14**	**R15**	**R16**
FMCC	Y				Y			Y	Y	Y	Y									
CCAT	Y				Y		Y		Y				Y							
RLPR	Y								Y			Y		Y	Y					
PF-WGTR	Y				Y	Y	Y	Y	Y											
AODV (AI-Hello)	Y				Y	Y		Y	Y							Y				
FARP	Y				Y	Y	Y		Y											
TARRAQ	Y				Y	Y	Y		Y											
MWCRSF	Y				Y	Y	Y	Y	Y	Y	Y				Y		Y			
OLSR-OMD		Y			Y				Y											
T-OLSR		Y			Y				Y											
QTAR		Y			Y	Y	Y		Y						Y					
EAPFL		Y			Y	Y			Y											Y
LECAR		Y			Y	Y	Y		Y				Y					Y	Y	
OLSR+		Y			Y	Y	Y	Y	Y											
MPR-FA		Y			Y	Y	Y	Y	Y											
MDRMA			Y		Y		Y		Y											
3DSRW			Y		Y			Y	Y											
AODV-HACO			Y		Y		Y	Y												
LS-AODV			Y		Y		Y		Y											
OEE-AODV			Y			Y		Y	Y			Y								
RGIM				Y	Y			Y	Y											
DLSA				Y	Y				Y						Y					

Note: A: Adaptive Routing Framework, P: Proactive Routing Framework, R: Reactive Routing Framework, H: Hybrid Routing Framework, R1: Packet Delivery Ratio, R2: Energy Consumption, R3: Routing Overhead, R4: Network Throughput; R5: End-to-End Delay, R6: Cluster Lifetime, R7: Cluster Formation Time, R8: Search Success Rate, R9: Hop Count, R10: Control Packet Overhead; R11: Network Lifetime; R12: Network Overhead; R13: Number of Clusters, R14: Number of Copies per Packet, R15: Number of Transmissions per Packet, R16: Route Stability.

VI. ROUTING FRAMEWORK

Over the years, there have been several factors and applications that have been used to test the performance of routing frameworks. From the recent literature that has been reviewed in section V, this section considers the frequency of

adoption of recurring parameters that are utilized to validate the performance of routing frameworks in FANETs. This analysis aims to assist researchers in quickly grasping essential technical aspects of the tools and metrics to take into account from recent studies on FANETs. Discussed in subsection VI (A-C) are the mobility models, performance measures, and tools generally considered in FANETs.

A. Mobility Models

The movement of UAVs is crucial to the operations of routing approaches and procedures in the dynamic environment of FANETs. The characteristics of these approaches generally impact the performance measures considered in evaluating routing frameworks. Fig. 2 illustrates the frequency of adoption of the mobility models in the literature considered for this paper. Most of the routing frameworks delineated in the literature considered for this work were selected for their effectiveness in mimicking the movement of UAVs. However, it was observed that Random way point had the highest level of adoption at 60%. A key reason for this was due to the flexibility and ease of the model in mimicking the movements of dynamic UAVs in FANETs. The next model which had a fairly high rate of adoption was the 3D Gauss-Markov model which had an adoption ratio of 20%. The remaining models identified from the literature considered had an adoption ratio of 5%, respectively.

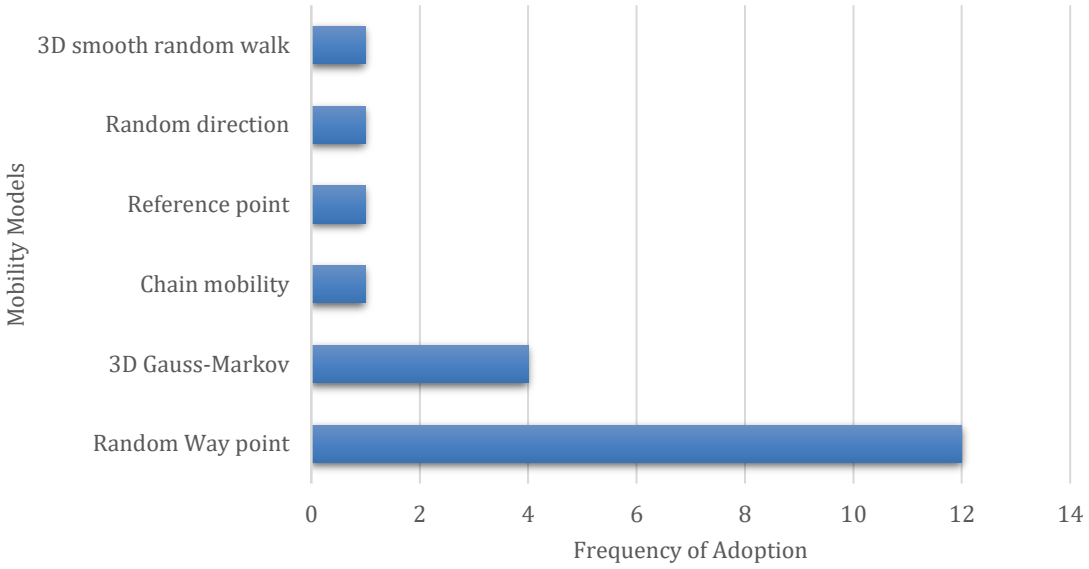

Fig. 2. Analysis of Mobility Models Used in Mimicking the Movement of UAVs in FANETs

B. Performance Measures

As highlighted in section V, there have been several research works that provide relevant insights into the modifications done to improve routing in FANETs. Regardless of the techniques, these proposed approaches sometimes utilize similar performance measures to determine the QoS offered by the routing frameworks proposed. As such, this section delineates the performance measures adopted in literature to improve routing frameworks to aid readers in capturing technical aspects related to the selection, modification, or usage of routing frameworks in FANETs. Presented in Fig. 3 is a comparison of performance measures adopted in the literature. From the results obtained, it is observed that E2E delay had the highest rate of adoption of 95% across the routing approaches in the literature. Following closely with about 90 % adoption rate was the PDR. Due to the critical importance of both metrics in preserving real-time communication, E2E delay and PDR are used as the main performance measures in evaluating routing systems for FANETs. Minimizing end-to-end delay in FANETs directly impacts the QoS and overall functionality of the network. When the measurement of this metric is low, factors such as timely decision making and situational awareness that improves the reliability of the network are optimized for high mobility UAVs, and the reverse is the case when the measure of this metric is high. This could deteriorate the routing performance, increase energy consumption, and routing overhead in the network. This metric is measured in seconds (s) or its subunits. The PDR, on the other hand, is particularly significant since it shows how well a routing protocol is able to create trustworthy paths and meet the Quality of Service (QoS) requirements necessary in critical situations like military and emergency applications.

For the other performance measures adopted in the literature considered for this paper, control packet overhead, number of clusters, number of copies per packet, number of transmissions per packet, and route stability had the lowest adoption with about 5%.

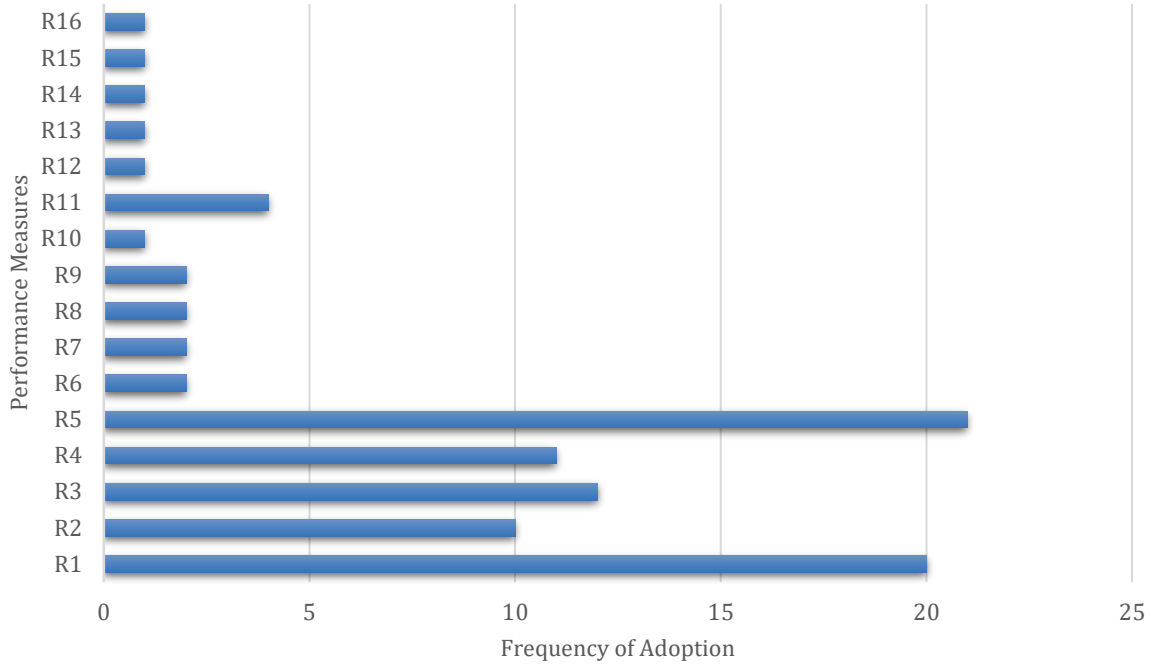

Fig. 3. Analysis of Performance Measures Utilized in Evaluating the QoS of Routing Frameworks in FANETs. R1: Packet Delivery Ratio, R2: Energy Consumption, R3: Routing Overhead, R4: Network Throughput; R5: End-to-End Delay, R6: Cluster Lifetime, R7: Cluster Formation Time, R8: Search Success Rate, R9: Hop Count, R10: Control Packet Overhead; R11: Network Lifetime; R12: Network Overhead; R13: Number of Clusters, R14: Number of Copies per Packet, R15: Number of Transmissions per Packet, R16: Route Stability

C. Simulation Tools

Researchers interested in FANETs technically invest in the logical design of routing frameworks to improve the routing framework of FANETs. To test the efficacy of these frameworks after design, the performance of these routing frameworks is tested in simulators to evaluate their performance in defined network scenarios. An analysis of the tools used for evaluating these routing frameworks is illustrated in Fig. 4. From the literature considered in this paper, it was observed that NS 3 had the highest number of adoptions of about 41%. This was due to its versatility in executing and evaluating algorithms as such it is more useful in evaluating the QoS performance of wireless Ad-hoc communication. Additionally, NS offered realistic simulation environments at the network layer, physical layer and MAC layer. Also, NS is open source. MATLAB was observed to follow closely with about 27% in adoption. Java and OMNet ++ were observed to have the lowest level of adoption with about 5% usage, respectively.

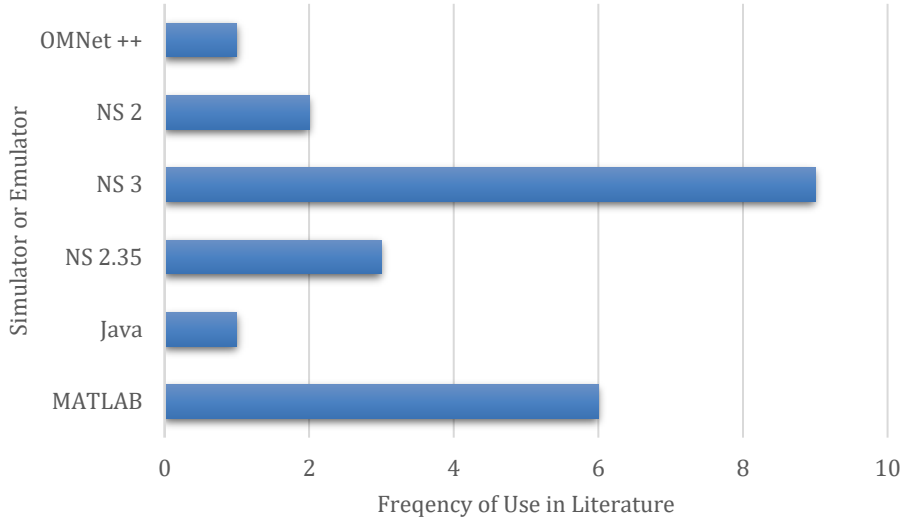

Fig. 4. Analysis of Simulators for Evaluating the Performance Measures of Routing Frameworks in FANETs

VII. Open Challenges and Potential Research Directions

As FANETs expand and proliferate in a variety of applications, such as aerial surveillance, environmental monitoring, disaster response, and communication relay, a number of important challenges and complexities arise. These obstacles span a wide range, from ensuring secure communication and mobility management in the context of autonomous aerial vehicles to resolving energy efficiency and security issues. The next subsections discuss the fundamental problems and potential research directions that influence the dynamic FANET environment.

A) Reduce the Impact of Regular Link Disconnections to Enhance Routing

Route discovery and maintenance to reconnect routes, as well as packet retransmission, can be increased by frequent link disconnections and network partitions [40]. This decreases the performance of the network, which can be undesirable in urgent situations like rescue and disaster relief operations [41]. Since the topology of the network is very dynamic, it presents a challenge to network connectivity, and due to its cost inefficiency which stems from higher computational and routing overhead. It is pertinent to address the issues aforementioned in order to likely increase QoS performance, reduce energy usage, and increase route setup success rate in FANETs. Furthermore, research could be done to lessen link disconnections and network partitions; for instance, a UAV's projected next location can be used to maintain a route or choose intermediate nodes of a route.

B) Assisting Multi-UAV Routing by Performing Clustering

Essential collaboration tasks, such as data aggregation, load distribution, resource allocation, and local synchronization, are carried out to accommodate the enormous amount of data generated by UAVs as a result of ultra-densification in the multi-UAV and multi-UAV swarm scenarios. In order to increase network stability and scalability, clustering (also known as hierarchical routing) divides nodes with similar traits and behaviours into logical groups; as a result, it is appropriate to support collaborative tasks [42]. Clustering can lengthen the lifetime of a network and also the stability and lifetime of a route [43]. Although clustering strategies have been put forth for FANETs [44], there hasn't been much attention paid to situations involving ultra-densification. Further research might be done to accomplish clustering utilizing context-aware methodologies, such as artificial intelligence approaches and bio-inspired algorithms, since the network densification varies with geographic locations and time [45].

C) The Investigation of Routing in FANETs Using Improved Mobility Models

As a result of the extremely dynamic movement patterns of UAVs in three dimensions and the potential for great distances between them, UAVs can experience link disconnection, which shortens the lifetime of a route. This could consequently lead to high cost and low residual energy in the UAV. Although movement with a high degree of mobility in a three-dimensional space is the fundamental feature of FANETs, an extensive mobility model that addresses the high cost and low residual energy needs to be further investigated.

D) Multi-Pathing Improves Network Performance and Survivability

Due to the high degree of dynamicity in the network architecture, there are frequent link disconnections and network partitions, which necessitate regular route finding and maintenance, which increases cost. Multiple routes can be used simultaneously to maximize resource utilization [46] and reduce network congestion, which is crucial under ultra-densification, additionally, a backup route is made available in the event that the current route fails to increase network survivability and fault tolerance, which reduces routing overhead]. Multi-pathing

establishes more than one route. Multi-pathing could be investigated further in order to enhance network performance and resilience.

E) Using artificial intelligence to boost network performance

A system can autonomously learn from its operational environment and prior experience using artificial intelligence (AI), such as deep learning and reinforcement learning, to enhance its performance over time. AI is essential for enhancing communication between flying nodes. As such, UAVs can self-organize and choose the best routes for themselves thanks to deep learning and reinforcement learning. To enhance routing performance in FANETs, more research should be considered using AI.

F) Green Energy's Role in Energy Consumption Reduction

UAVs may be widely dispersed and are extremely dynamic in three-dimensional space, which results in frequent link disconnection and network partitions that shorten route lifespan. As a result, setting up and choosing routes occasionally requires a lot of energy. Mechanisms based on green energy could likely cut down on energy use. In order to conserve energy, fewer messages are exchanged between UAVs. How UAVs can work together for energy gathering might be the subject of further research as this could keep the UAVs alive for longer durations.

VIII. CONCLUSION

In this paper, a comprehensive review of existing routing frameworks for FANETs was considered. This systematic review was done in order to delineate the gaps in the existing routing frameworks considered and present likely areas for future research design improvements, which could mitigate routing overhead and improve failing routing performance due to the dynamic nature of nodes. And effectively improve cluster energy management and load-balanced data routing system to reduce network outages. As such, this review discusses the features of mobility models, routing metrics, and routing frameworks. The analysis of the aforementioned features highlighted that the random waypoint mobility model had the highest frequency of adoption due to the flexibility and ease of the model in mimicking the movements of dynamic UAVs in FANET regardless of the routing framework. In relation to the QoS, performance measures such as energy consumption, routing overhead, and network throughput were essential. However, the frequency of adoption of end-to-end delay clearly indicated the metrics in determining the other metrics considered in the dynamic topology of FANETs. Additionally, the PDR, on the other hand, is particularly significant since it discusses the trustworthiness of routing which are critical situations like military and emergency applications. In the same vein, the versatility in executing and evaluating algorithms makes the NS 3 tool a more likely tool in evaluating the QoS performance of wireless ad-hoc communication. Since, NS offered realistic simulation environments at the network layer, physical layer and MAC layer. Also, NS is open source. The analysis carried out is expected to save time and resources for researchers, engineers, and policymaker in making informed evidence-based decision-making on routing protocols to adopt or improve.

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