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# Routing in Flying Ad Hoc Networks: Survey, Constraints, and Future Challenge Perspectives

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**ABSTRACT** Owing to the explosive expansion of wireless communication and networking technologies, cost-effective unmanned aerial vehicles (UAVs) have recently emerged and soon they will occupy the major part of our sky. UAVs can be exploited to efficiently accomplish complex missions when cooperatively organized as an ad hoc network, thus creating the well-known flying ad hoc networks (FANETs). The establishment of such networks is not feasible without deploying an efficient networking model allowing a reliable exchange of information between UAVs. FANET inherits common features and characteristics from mobile ad hoc networks (MANETs) and their sub-classes, such as vehicular ad hoc networks (VANETs) and wireless sensor networks (WSNs). Unfortunately, UAVs are often deployed in the sky adopting a mobility model dictated by the nature of missions that they are expected to handle, and therefore, differentiate themselves from any traditional networks. Moreover, several flying constraints and the highly dynamic topology of FANETs make the design of routing protocols a complicated task. In this paper, a comprehensive survey is presented covering the architecture, the constraints, the mobility models, the routing techniques, and the simulation tools dedicated to FANETs. A classification, descriptions, and comparative studies of an important number of existing routing protocols dedicated to FANETs are detailed. Furthermore, the paper depicts future challenge perspectives, helping scientific researchers to discover some themes that have been addressed only ostensibly in the literature and need more investigation. The novelty of this survey is its uniqueness to provide a complete analysis of the major FANET routing protocols and to critically compare them according to different constraints based on crucial parameters, thus better presenting the state of the art of this specific area of research.

**INDEX TERMS** UAV, FANET, mobility, simulation, routing protocols.

## I. INTRODUCTION

With more and more Unmanned Aerial Vehicles (UAVs) flying over our heads, there is an ever-increasing need for coordination, communication, safety, and information sharing among these devices in order to be a practical choice for various applications including search and rescue, patrolling, delivery of goods, and military [1]. Moreover, due to their large coverage and their ease of installation, UAVs can be used as wireless relays, flying sensors, on even aerial base stations [2]–[4]. To efficiently accomplish a given application

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in a timely manner, a group of cooperative UAVs rather than a single UAV has to be spread over the area of interest, thus enhancing the multitasking ability, increasing the network lifetime, and growing the scalability [5], [6]. Nevertheless, some challenging issues are distinguished caused, *e.g.*, by the high mobility of UAVs and their sparse deployment [7]. One of the most complicated problems is the exchange of information between UAVs that suffers from severe losses.

### A. MOTIVATION

A reliable communication or what is referred to as a routing protocol between UAVs constitutes a building block of

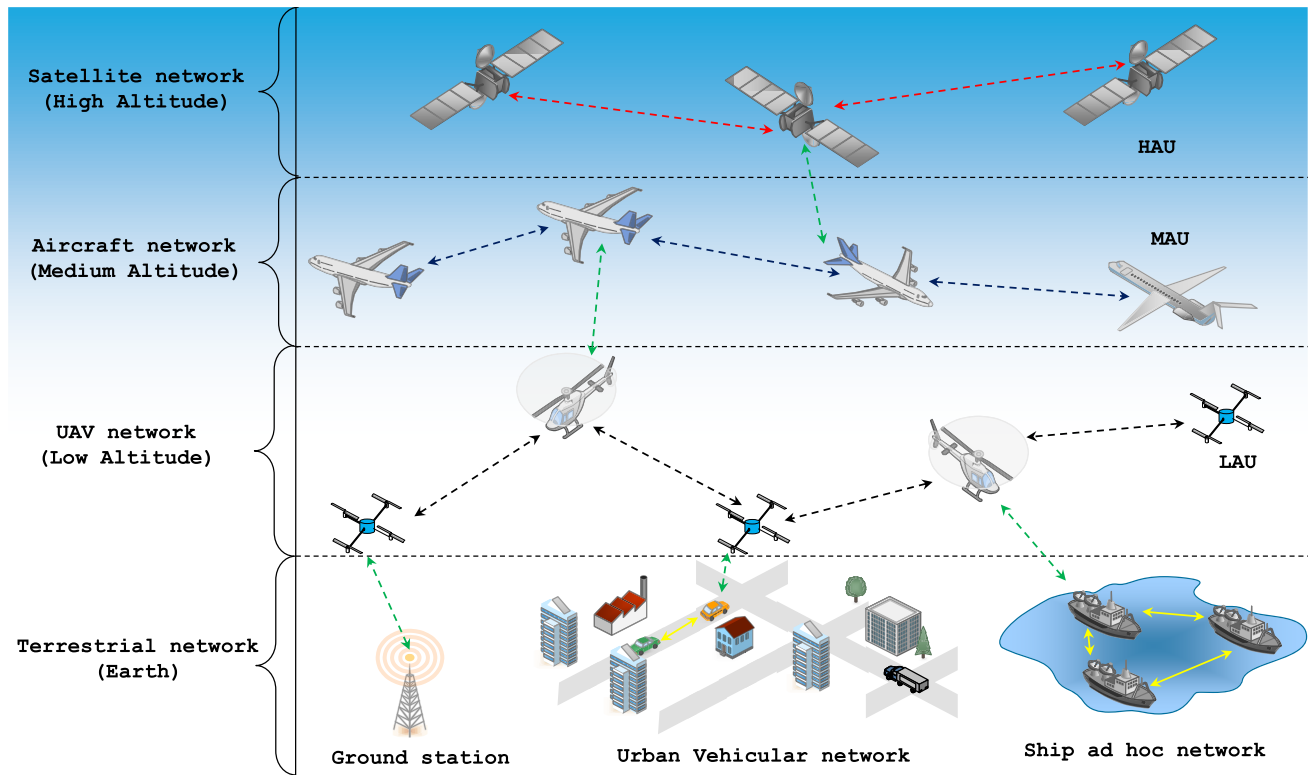


FIGURE 1. Overview of FANET categorization.

the data delivery in each application [8]. Therefore, a well-designed networking model needs to be defined, which allows UAVs to communicate with each other and to self-organize themselves into a network, called Flying Ad hoc Network (FANET) [9], [10]. Although similar to both Mobile Ad hoc Network (MANET) and its sub-classes, FANET extends its conception in order to be able to forward packets, gather, and share information [11]. Nevertheless, several challenging characteristics are distinguished in the behavior of UAVs, which should be well-respected, such as their high mobility, their unpredictable movements, and their non-uniform distribution over the network, which results in frequent topology changes, and therefore, makes the design of FANET routing protocols a very complicated task [12].

To support the growing number of FANET applications and to keep their functioning reliable and stable, the incremental design of routing protocols becomes mandatory to address the aforementioned issues and to take care of the unique characteristics of FANETS [13]. As a result, a large number of routing protocols using different techniques are proposed for FANETS trying to provide concurrent performances, to avoid packet losses, and to be able to adapt to different scenarios and situations. Furthermore, due to its similarity with MANETs, researchers have studied the possibility to apply the routing techniques used in those environments in FANETS [14]. However, even if some modifications have been made, different requirements are overlooked, such as

the mobility patterns, the energy constraints, the area of deployment, the node localization, and the QoS requirements. Consequently, the knowledge of the different routing protocols' limits and the existing techniques allow us to always develop new routing schemes, according to the needs and to know which near-optimal methods to apply among UAVs in a given situation.

### B. UAV CATEGORIZATION

As depicted in Figure 1, UAVs in FANETS are naturally classified based on their altitudes, into high altitude UAVs (HAUs), medium altitude UAVs (MAUs), and low altitude UAVs (LAUs) [43]. HAUs have altitudes above 20 km and they are almost stationary, such as satellites, airship, and hot air balloon. MAUs fly at medium altitudes up to 11 km, such as aircraft, and they move more quickly from the point of view of ground nodes. As for LAUs, their altitudes reach few kilometers and are highly mobile, such as drones or copters.

Traditionally, FANET is generally managed by a control station, such as a ground base station or a satellite, which are used for communication and to share critical information [44]. There are some particular UAVs that are designated according to several features to communicate with ground stations, ground mobile nodes (e.g., vehicles or ships), and satellites, thus achieving UAV-to-UAV (U2U) communications via the infrastructure [45]. Nevertheless, the infrastructure-based concept exhibits various

**TABLE 1.** FANET surveys related work.

Surveys		Architecture	Routing Techniques	Routing protocols	Routing taxonomy	Mobility models	Number of protocols	Popularity	Comparisons	Future challenges	Description
2019	Ref. [15]	√	×	√	√	×	18	New	√	√	Studied cluster-based routing protocols for FANETs along with different routing issues.
	Ref. [16]	×	×	√	×	×	10	New	×	√	Studied FANET issues and challenges and a small number of routing protocols are described.
	Ref. [17]	×	×	×	×	×	–	New	×	√	Briefly investigated FANET basic concept and explained various challenges and applications.
2018	Ref. [18]	√	×	√	×	×	3	New	√	√	Surveyed issues and mechanisms of high and low altitude platforms communication networks.
	Ref. [19]	×	×	√	×	×	10	New	√	×	Presented a review of VANET and FANET adopting nature-inspired optimization mechanisms.
	Ref. [20]	×	×	√	√	×	9	New	√	×	Provided the design issues of FANETs along with the communication methodologies and routing protocols.
	Ref. [21]	√	×	×	×	√	–	New	√	×	Presented the architecture, the applications, the simulators, and the mobility models of FANETs.
	Ref. [22]	×	×	√	√	×	8	New	√	×	Focused on topology-based routing protocols in the context of FANETs.
	Ref. [23]	×	×	×	×	×	–	New	×	×	Surveyed different computational intelligence algorithms used in UAV path planning.
	Ref. [24]	×	×	×	×	√	–	New	√	×	Reviewed mobility models, positioning and propagation models dedicated for FANETs.
	Ref. [25]	√	×	×	×	×	–	New	×	×	Surveyed literature concerning UAV swarm and proposed a swarm architecture using cellular network.
	Ref. [26]	×	×	√	√	×	15	Medium	√	√	Presented the most popular FANET routing protocols and their performances comparison.
	Ref. [27]	×	×	√	×	×	13	Medium	√	√	Presented both the main features of aerial and aquatic vehicular networks and the open challenge issues.
2017	Ref. [28]	√	√	√	√	√	16	High	√	√	Surveyed position-based FANET routing protocols and compared them based on crucial parameters.
	Ref. [29]	√	×	√	×	×	6	Low	√	√	Discussed and compared cooperative FANET approaches along with their software solutions.
	Ref. [30]	√	×	×	×	×	–	Medium	×	√	Identified the main privacy, security, and safety aspects associated to FANETs.
	Ref. [31]	×	×	√	√	×	26	Low	×	√	Collected the most popular FANET routing protocols.
	Ref. [32]	√	×	√	×	×	14	Low	×	√	Included the communication FANET architecture and an overview of FANET routing protocols.
	Ref. [33]	√	×	√	√	√	30	Medium	√	√	Highlighted the FANET characteristics and provided a review of FANET secure routing protocols.
2014	Ref. [34]	√	×	√	×	×	4	High	×	√	Surveyed both FANET architecture and distributed gateway selection and cloud-based algorithms.
	Ref. [35]	√	×	×	×	√	–	High	√	√	Surveyed different FANET requirement, such as connectivity, security, scalability, and QoS.
	Ref. [36]	√	×	√	×	×	24	High	√	×	Elaborated the majority of FANET issues along with their future perspectives.
2013	Ref. [37]	√	×	√	×	×	9	High	×	√	Highlighted the challenges when using UAVs as relays and depicted the open challenges.
	Ref. [38]	×	×	×	×	√	–	Medium	√	√	Presented the different FANET mobility models and their evaluations.
2013	Ref. [39]	√	×	√	×	×	10	High	√	√	Introduced the main design challenges of FANETs along with existing protocols.
	Ref. [40]	×	×	×	×	×	–	Low	×	×	Briefly described both the FANET issues and the open future challenges.
	Ref. [41]	√	×	√	×	×	7	Medium	×	√	Depicted the challenges of using UAVs as mobile nodes in an ad hoc fashion.
	Ref. [42]	×	×	×	×	×	–	High	×	×	Surveyed UAV-based systems dedicated for traffic monitoring management.
Our survey		√	√	√	√	√	60	–	√	√	Describes FANET architecture in an original way and picks out the different challenges and issues. Moreover, it surveys the majority of FANET routing protocols, mobility models, and simulators.

limitations, such as the hardware requirements, the reliability of communication, and the restricted coverage of both UAVs and the infrastructure.

As a solution, the network should be organized in an ad hoc fashion while establishing multi-hop connections between the communicating nodes. In this way, each UAV can communicate with another one or the infrastructure through a succession of UAVs, all constituting an ad hoc network. Due to the highly dynamic topology, FANETs require sometimes peer-to-peer connections between the nodes.

**C. SHORTCOMINGS OF THE LITERATURE AND OUR CONTRIBUTIONS**

Since the beginning of this decade, an exponential growth of survey papers handling FANET issues has been witnessed. However, none of them has focused so far on the routing issues except a few studies that have superficially addressed the routing in FANETs along with other issues. TABLE 1 provides a comparative study based on crucial points that have to be tackled in routing between the majority of existing surveys in the literature and our survey. With the perpetual expansion of this research, this survey is one of the first

comprehensive guides on how to exploit the potential of UAVs and to correctly manage the exchange of information between them. For this purpose, our survey is organized as follows:

- In Section II, we define FANET as a distinct ad hoc network along with its architecture. This allows to make a comparative study between the unique features of FANETs and MANET sub-classes.
- In Section III, we deeply describe and compare the existing mobility models that are either designed exclusively for FANETs or adapted to.
- In Section IV, we present the major routing techniques used in FANETs, their features, and their complexity. Each routing technique is illustrated by an explanatory figure.
- In Section V, based on a novel and original taxonomy, we present a comprehensive survey of the majority of routing protocols applied or exclusively developed to FANETs and classified based on nine categories: (i) Topology-based, (ii) Secure-based, (iii) Swarm-based, (iv) Hierarchical-based, (v) Energy-based, (vi) Heterogeneous-based, (vii) Position-based,

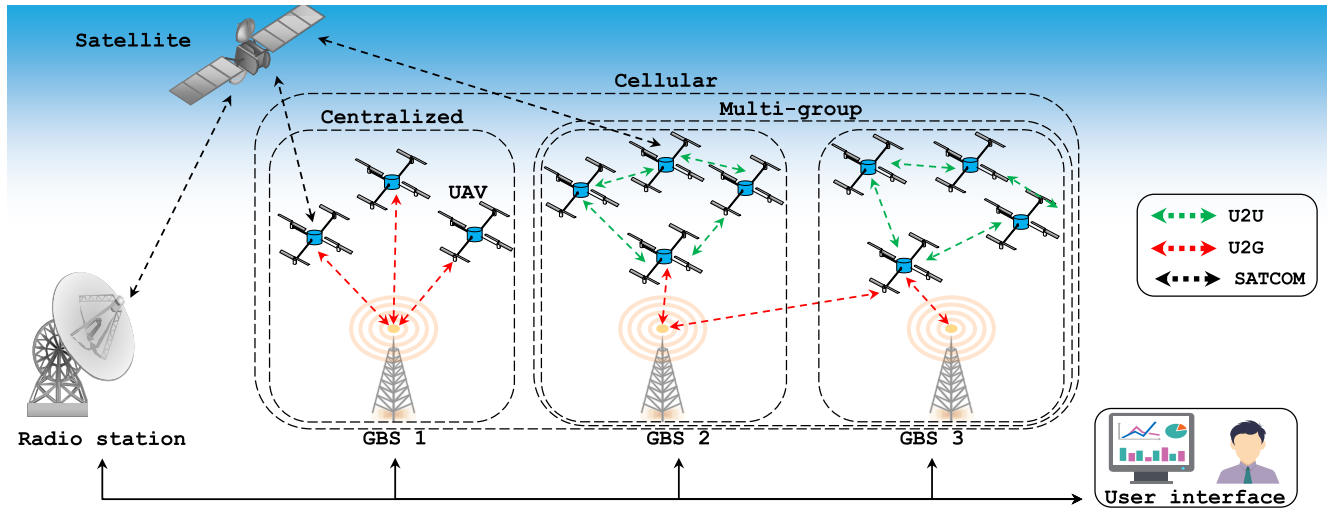


FIGURE 2. FANET architecture.

(viii) DTN-based, and (ix) Cross-layer-based. Each protocol is described using a concrete example that is illustrated by a figure. A critical description is provided for each category based on a comparative study.

- In Section VI, we then provide a global comparative analysis of the discussed FANET routing protocols, which allows us to have an overview of the adopted routing strategies, the different requirements, the features, and the type of experimental validation to be used.
- In Section VII, we outline the challenging open issues that should be addressed in order to fully exploit the potential of FANET applications.
- Finally, Section VIII concludes this survey with additional perspectives and insights for more investigations on this hot topic of research.

## II. FANET ARCHITECTURE

FANET is set of UAVs and ground base stations (GBSs) autonomously connected with each other, without a pre-existing communication configuration [46]. That is, the communication between these entities should be done in an ad hoc fashion in which UAVs and GBSs are all involved in the data transmission [47]. Generally, this system selects specified UAVs having further capabilities to act as gateways between GBSs and other UAVs, thus extending significantly the network coverage [48]. Additionally, different kinds of communications are used, different network organizations are applied, and different features are required for different applications [49]. To this end, this section is divided into three subsections. The first one is devoted to the major FANET organizations commonly adopted across the literature. Secondly, different FANET communications are described. Finally, the unique characteristics and features of FANETs are detailed. For each description, we always refer to Figure 2 throughout the following subsections.

### A. FANET ORGANIZATION

Designing a fully cooperative FANET system requires a set of mechanisms and rules that define how information has to be exchanged between UAVs and GBSs. There are a number of communication organizations that are used according to the applications that UAVs plan to accomplish [50]. However, to the best of our knowledge, there are no enough convincing researches that definitively determine what organization would work best. Therefore, in this subsection, we analyze the centralized, the multi-group, and the cellular organizations, which are frequently used in the majority of applications (*c.f.*, Figure 2). Moreover, we highlight their strengths and weaknesses.

#### 1) CENTRALIZED ORGANIZATION

All UAVs are directly connected to one or more GBSs that can communicate with each UAV simultaneously. Since inter-UAV communications are not possible, all data traffic has to be routed through GBSs [51]. Such an organization has many benefits, such as the increase of the fault tolerance in the case of UAV failure, the parallelism of tasks, and the enhancement of the calculation and storage capabilities. Nevertheless, due to its centralized nature, this organization has three major flaws. First, since there is a dedicated bandwidth for each UAV, the total amount of bandwidth is expected to proportionally scale with the increasing of UAVs, thus requiring more expensive bandwidth downlinks. Second, the high latency caused by the centralization of the traffic through GBSs. Finally, a GBS constitutes a single point of failure representing a vulnerability against failures and attacks, in which its breakdown can disrupt the overall network.

#### 2) MULTI-GROUP ORGANIZATION

In this organization, UAVs have the possibility to communicate with each other in an ad hoc manner while conserving

the centralized organization. Moreover, multiple groups are formed wherein each one designated UAVs play the role of gateways connecting the groups to the GBSs [52]. The communications inside the groups are carried out without involving GBSs, but the inter-group communications are performed through the GBSs. This organization provides better performance compared to the centralized one in which a large number of UAVs having different communication and flight features is supported. However, due to the semi-centralized nature of this organization, the problem of reliability still exists since certain data traffic transits through GBSs. Furthermore, the failure of a given GBS can cause the problem of network partition, thus isolating a group of UAVs from the rest of the network.

### 3) CELLULAR ORGANIZATION

The cells provided by GBSs, which contain UAVs can be considered as a promising solution to ease the deployment of many civilian and military applications. A unique frequency is used by each cell to avoid interference between each other [53]. Combined together, cells can provide an important signal coverage over a specific area [54]. In such an organization, UAVs can directly communicate with each other or communicate via GBSs. However, cells are not a cost-effective solution due to the expensive implementation of GBSs that are deployed only when the mission area is known beforehand. Moreover, this organization vulnerable due to the fixed GBSs that can fail at any time, causing the complete loss of control on many or on all UAVs. Consequently, several challenges have to be carefully studied before the widespread deployments of cellular networks.

## B. FANET COMMUNICATION

According to the FANET's organizations discussed above, each node in the network (*i.e.*, UAV, GBS, and Satellites) can act as an end system [55]. However, the communication of two distant nodes is exposed to different constraints, such as the sudden disconnections, the packet losses, and the permanent fragmentation of the network. Therefore, all these nodes can cooperate and organize themselves as relays in order to cope well with the frequent topology variation [56]. Thus, this arises three types of communication to consider in FANETs: (i) UAV-to-UAV, (ii) UAV-to-Ground, and (iii) Satellite Communication. These communications are discussed in more detail in the subsequent sections.

### 1) UAV-TO-UAV (U2U) COMMUNICATION

To satisfy the needs of different missions, UAVs directly communicate by frequently exchanging data packets with each other. However, due to the restrictions on the transmission ranges, multi-hop communication is carried out over other UAVs. This is crucial to extend the coverage of a specific area of interest. In the majority of cases, the line-of-sight (LoS) is predominant in U2U communications since no obstructions exist between UAVs in the sky [57]. Nevertheless, there are exceptional cases where line-of-sight is not guaranteed,

especially when UAVs are exposed to high rise buildings or mountains.

### 2) UAV-TO-GROUND (U2G) COMMUNICATION

For a better control of flying UAVs, infrastructures in the form of GBSs are fixed on the ground in order to exchange critical control and command messages [58]. In addition, GBSs are also used to link different groups of UAVs between each other. Generally, there are specific UAVs that are able to communicate with GBSs in order to decrease the congestion of the network and to enhance throughput and connectivity. If UAVs fly at high altitudes, the LoS is predominant in U2G links. However, at low altitudes, UAVs do not ensure an LoS with GBSs due to the existing obstructions on the ground causing the reflections and diffraction phenomena [59].

### 3) SATELLITE COMMUNICATION (SATCOM)

UAVs are often deployed in complex environments, such as ocean and mountainous areas, where it is difficult to install GBSs. Moreover, when a FANET requires continuous connectivity and the network is severely partitioned, there is a need for a centralized entity ensuring permanent connectivity. Satellites can be an adequate option to serve as relays controlling UAVs in a centralized manner and also providing an important LoS coverage, thus establishing Satellite Communication (SATCOM) [60]. SATCOM is beneficial to both support the exchange of critical data between UAVs and delivering collected information to a radio station located far apart on the ground. However, this is not a cost-effective solution.

TABLE 2 provides a brief comparison between the discussed types of FANET communications.

TABLE 2. FANET communication comparison.

	U2U	U2G	SATCOM
LoS	High	Medium	High
Cost	Cheaper	Expensive	Highly expensive
Coverage	Medium	Large	Huge
Exploitation	Short-term	Mid-term	Long-term

## C. FANET CHARACTERISTICS

Each mission or application comes with different requirements in terms of the number of UAVs, the flight time, and the communication constraints. This diversifies the characteristics of FANETs and makes them unique, which differentiate them from other kinds of ad hoc networks. In this section, we provide a detailed description of the most crucial FANET characteristics that are considered during the deployment of such networks.

### 1) NODE SPEED

The LAUs are considered as the most studied categories of UAVs. In this category, we distinguish two kinds of UAVs: (i) Rotary-Wing (RW) UAVs and (ii) Fixed-Wing (FW) UAVs [61]. In a general case, the mobility of both types of

UAVs are both deployed in a two or three-dimensional space (2D or 3D) and controlled according to the mission. Their movements are highly dynamic, from being static (*e.g.*, in aerial monitoring or coverage) to a full speed flying (*e.g.*, in delivering of goods or search and rescue mission). Their speeds vary from 0 to 100 m/s, thus resulting in many challenging communication issues. TABLE 3 shows a comparison between RW and FW UAVs in terms of mobility.

**TABLE 3. FW and RW UAVs.**

	FW-UAVs	RW-UAVs
Speed	Up to 100 m/s	Up to 30 m/s
Static Hovering	No	Yes
Altitude	Med-Low	Low
Movement degree	Low	High

## 2) DENSITY

Density can be defined as the average number of UAVs in a unit zone. Based on the kinds of UAVs and the objective of their applications, the density of UAVs can be varied from low to extremely dense. If UAVs have the ability to both provide a large transmission range and move at high speeds, their density can be very low and the distance between them can reach several kilometers [62]. Otherwise, there is a need to deploy a large number of UAVs cooperating with each other using algorithms to achieve a given mission.

## 3) GROUND BASE STATION (GBS)

Consisting of a transmitter and receiver, a GBS is able to send or to collect flight data traffic (*e.g.*, speed, altitudes, and battery status) [63]. A GBS can both communicate with all UAVs in range and calculate the quality of the communication links between each other. Furthermore, the GBS is also responsible to send commands, such as the desired altitudes, the processing levels, the appropriate speed, *etc.*

## 4) USER INTERFACE

More often, the movements of UAVs are manually controlled by a radio remote controller. However, sometimes, it is required that users have real-time monitoring and area awareness, and especially when UAVs are out of their eyesights. User interfaces are developed and executed on computers that are directly connected to GBSs [64]. They allow users to both determine the tasks to be achieved and set certain properties, such as the update intervals. Moreover, the users have the ability to modify the tasks as needed according to the situation or the events occurred in the area.

## 5) LUNCH SYSTEM

This system provides to UAVs their initial flight speeds in a very short distance and time. For instance, RW-UAVs are generally launched by the hands while FW-UAVs need in most cases an airfield for take-off and landing.

## 6) PROPAGATION MODEL

The radio propagation characteristics are crucial for the development of any communication system. FANETs have their own characteristics, such as the movement effects,

ground reflection impacts, and a high possibility of Line-of-Sight (LoS) between UAVs, which allow a mathematical modeling of each case channel. A set of channel models has been proposed for each case of communication, and especially U2U channels [65], [66] and U2G channels [67], [68]. The most popular and simplest propagation model, according to several simulation experiments is the Friis free space model [69].

## 7) FREQUENCY BAND

The majority of UAV communication systems are supported by unlicensed bands, such as 0.9 GHz [70] and 2.4 GHz [71], which are considered as inadequate since they can be quickly congested with other communication systems [72]. It is demonstrated that U2G links can be best deployed using 5 GHz frequency with IEEE 802.11a standard devices [73]. Furthermore, to avoid the interference with other bands, 5.9 GHz band is considered as the most suitable especially when it is used with IEEE 802.11p [74], [75].

## 8) ENERGY AUTONOMY

The energy consumption constitutes one of the major issues in FANETs. This is because UAVs are powered by embedded batteries having a restricted energy capacity [76]. The consumption varies depending on the type and size of UAVs, which is due to the fact that the energy required for the UAV propulsion is much greater than that needed for communication [77]. Consequently, the design of communication systems should consider the consumption efficiency to both increase the network lifetime and avoid sudden UAV failures.

## 9) LOCALIZATION

Since the UAVs move at high velocities, and in certain cases, with unpredictable mobility, FANET requires accurate localization with extremely short time update intervals. GPS is considered to be unsuitable for certain FANET protocols (*e.g.*, delivery of goods, collision avoidance, construction, *etc.*), since position information is updated at one second interval [78]. For these purposes, two categories of localization methods are proposed: (i) Network-based positioning which is based on the exchange of packets [79], and (ii) Height-based positioning which is based on the altitudes of UAVs [80].

## 10) COVERAGE

UAVs provide an effective solution to cover a large area, as in the mapping or monitoring scenarios. Moreover, UAVs can play a role of temporal connectivity coverage to ground users when the terrestrial infrastructures are damaged [81]. For an effective coverage, UAVs are based on various positioning techniques according to the kind of applications where UAVs are deployed for [82].

## 11) WIRELESS TECHNOLOGY

Different wireless technologies are used in FANETs, which are diversified depending on the wireless channel characteristics. The most commonly used wireless technologies

TABLE 4. Comparison between MANET subclasses.

	WSNs	VANETs	RANETs	SANETs	FANETs
Node type	Sensor devices	Car, Bus, Motorbike, Truck	Robot	Ship, Boat, Underwater vehicle, USV (Unmanned Surface Vehicle), Vessel	Drone, Aircraft, Copter, Satellite
Node speed	Static to lower (Average 0-6 km/h)	Medium to high (Average 20-130 km/h)	Static to medium (Average 0-20 km/h)	Medium to high (Average 20-130 km/h)	Low to high (Average 6-460 km/h)
Node Density	<ul style="list-style-type: none"> <li>Low</li> <li>Depends on the application</li> </ul>	<ul style="list-style-type: none"> <li>High</li> </ul>	<ul style="list-style-type: none"> <li>Low</li> </ul>	<ul style="list-style-type: none"> <li>Medium</li> </ul>	<ul style="list-style-type: none"> <li>Low</li> <li>Depends on the application</li> </ul>
Mobility	<ul style="list-style-type: none"> <li>Static or low</li> <li>2D or 3D</li> <li>Predefined trajectories</li> </ul>	<ul style="list-style-type: none"> <li>Regular</li> <li>2D</li> <li>Random trajectories</li> </ul>	<ul style="list-style-type: none"> <li>Free</li> <li>2D or 3D</li> <li>Controlled trajectories</li> </ul>	<ul style="list-style-type: none"> <li>Free or limited</li> <li>2D</li> <li>Predefined trajectories</li> </ul>	<ul style="list-style-type: none"> <li>Free</li> <li>3D</li> <li>Random or predefined trajectories</li> </ul>
Coverage	Low	Medium	Low	Medium	Low
Propagation model	<ul style="list-style-type: none"> <li>On the ground</li> <li>Low LoS</li> </ul>	<ul style="list-style-type: none"> <li>On the ground</li> <li>Low LoS (in urban area)</li> </ul>	<ul style="list-style-type: none"> <li>On the ground</li> <li>Low LoS</li> </ul>	<ul style="list-style-type: none"> <li>On the water</li> <li>High LoS</li> </ul>	<ul style="list-style-type: none"> <li>In the air</li> <li>High LoS</li> </ul>
Fixed Infrastructure	Sink	RSUs	Controller	Controller	GBS
Launch system	Placement	Roads	Placement	Water	<ul style="list-style-type: none"> <li>Hands</li> <li>Airfield</li> </ul>
Connectivity	Medium	<ul style="list-style-type: none"> <li>High hours (Rush hours)</li> </ul>	Low	Low	Low
Energy autonomy	Low	High	Low	High	<ul style="list-style-type: none"> <li>High (Depends on the UAV)</li> </ul>
User interface	Data gathering	Traffic monitoring	Data analyzing	Data transmission	Mission progress
Localization	GPS	GPS	GPS	GPS	GPS/Net/Height
Wireless technology	IEEE 802.15.4	IEEE 802.11p	IEEE 802.11	IEEE 802.11a/p	IEEE 802.11a/b/g/ac/s/n/p
Frequency band	2.4 GHz	5.9 GHz	2.4 GHz	5/8 GHz	2.4/5 GHz

are supported by IEEE 802.11, IEEE 802.15.4, and infrared standards. IEEE 802.11 standards are commonly called Wi-Fi, in which IEEE 802.11ac/n/s/b/g/a/p are used in several studies in FANETs [83]–[88]. IEEE 802.15.4 and Infrared standards are mostly used in indoor scenarios where small UAVs have short communication ranges [89]–[91].

environments where they are deployed. Each type of networks has specified characteristics, faces unique challenges, and deals with different issues. In this section, we define each sub-category of MANETs along with its functionality. Moreover, TABLE 4 complements this study by providing the characteristics of each category, while highlighting dissimilarities and similarities among them based on the characteristics already described in Section II-C and other crucial ones.

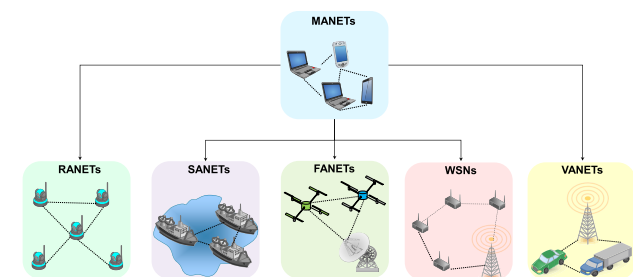


FIGURE 3. MANET and its sub-classes.

D. COMPARATIVE ANALYSIS

As illustrated in Figure 3, MANETs are sub-divided into five different networks depending on the type of nodes and the

1) WIRELESS SENSOR NETWORKS (WSNs)

These data-centric networks are formed by miniature and low-cost devices. The last ones are known as sensors that have the ability to both sense data from the surrounding environment and wirelessly communicate it to a central device, called a Sink [92]. WSNs can be applied in different industrial, residential, and civil applications. Since sensors have a restricted energy capacity, different mechanisms are proposed in the literature to efficiently manage energy consumption in order to increase the WSNs’ lifetime [93].



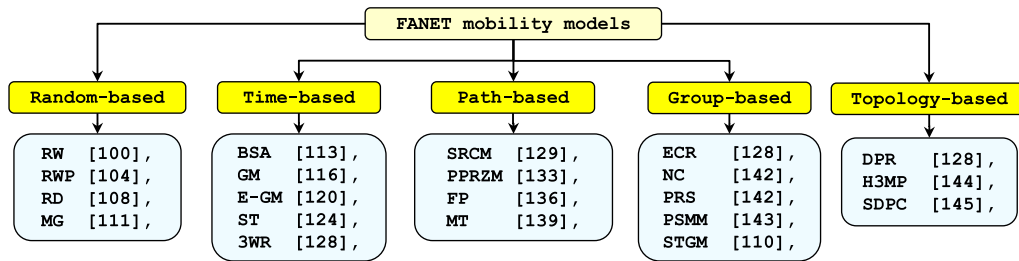


FIGURE 4. Taxonomy of FANET mobility models.

## 2) VEHICULAR AD HOC NETWORKS (VANETs)

These networks are a special kind of MANETs in which the mobile nodes are moving vehicles. These vehicles have unrestricted energy and computational capacity and they are characterized by their high mobility that is predictable and limited by road patterns [94]. The communication is carried out among vehicles and between road side units (RSUs) placed along the roads and vehicles, which are all wirelessly connected. VANETs are considered as a fundamental technology supporting road-safety as well as comfort applications.

## 3) ROBOT AD HOC NETWORKS (RANETs)

Since robots can be composed of transceivers, they are most likely to form a wireless ad hoc network without relying on centralized entities, which is called Robotic Ad hoc Network (RANET) [95]. Generally, the movement of robots can be intelligently controlled to maintain the connectivity of the network while ensuring a high ratio of data delivery. The energy capacity of robots is restricted, which impose wise management of the power consumption among them [96].

## 4) SHIP AD HOC NETWORKS (SANETs)

The main purpose of these large-scale networks is to extend the coverage of the maritime connectivity among ships [97]. Since there are different real-time applications supported by SANETs, they are mainly affected by the signal propagation delay, thus disturbing the synchronization performance. Therefore, reliable multi-hop synchronization mechanisms have to be developed to support the communication among thousands of ships in the maritime environment.

## III. FANET MOBILITY MODELS

Another challenging issue in FANETs is the mobility model that depicts the movements of UAVs in a specified area (*i.e.*, the variations in their direction, the speed, and the acceleration over the time.) [98]. The mobility allows UAVs to be adapted to the requirements of each application, thus providing better performance and greater flexibility. In the simulation side, mobility models are able to emulate in a realistic way the behaviors of UAVs in order to obtain outcomes as real as possible before a real deployment and test [99]. In the literature, there are some classical MANET mobility models that have been used in the evaluation of FANETs and several

others are specifically designed for FANETs. In this section, as illustrated in Figure 4, we divide the existing mobility models into five categories: (i) Random-based, (ii) Time-based, (iii) Path-based, (iv) Group-based, and (v) Topology-based. Then, we thoroughly review existing mobility models in each category, each with an explanatory figure. In the end, a global comparative study is provided summarizing the features of each mobility model, the application where it can be deployed, and its main ideology.

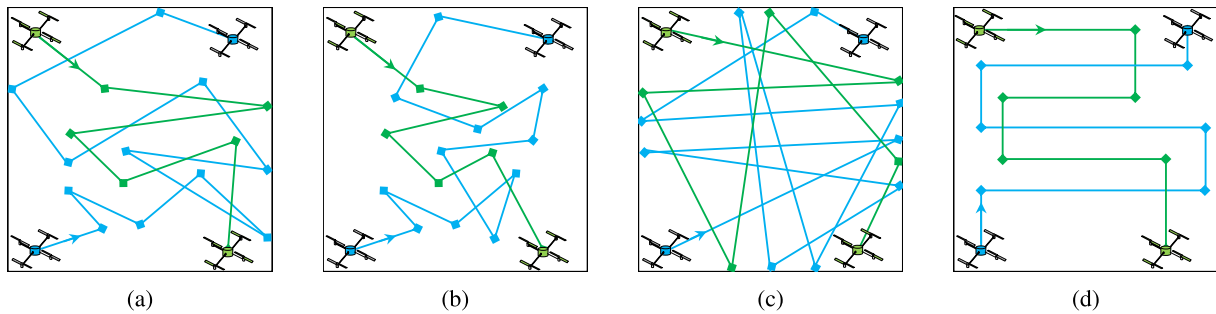
### A. RANDOM-BASED MOBILITY MODELS

Due to its simplicity, this kind of mobility models has been adopted to define the movements of UAVs and to evaluate the performance of FANETs. Indeed, each UAV randomly selects its motions completely independent of other UAVs. The movements are randomized in terms of speed, direction, distance, and time of movement.

RW (Random Walk) [100] is a random-based model allowing mobile nodes, at each fixed duration of time  $t$ , to select a random direction, speed, and distance. The latter parameters are selected from predefined ranges and re-calculated at the end of each movement. If a mobile node reaches the area boundary, it bounces off the boundary with a new direction. As illustrated in Figure 5(a), RW generally shows sudden changes of direction. During the change of direction, a new selected direction is decorrelated from the current direction. This model is adopted in many FANET protocols and applications, such as in [101]–[103].

RWP (Random WayPoint) [104] uses the same principle like RW [100], but it adds pause times between any changes of directions. Each mobile node starts by staying at a given position before the expiration of the pause time that is fixed at a certain value. After its expiration, a random direction, speed, and distance are selected randomly and the process is repeated until the end of the simulation time. As shown in Figure 5(b), unlike RW, the mobile nodes frequently appear towards the area of interest center. RWP is deployed in several protocols involving UAVs hovering at the same altitudes [105]–[107].

RD (Random Direction) [108], [109] is designed to address the density waves due to the non-uniform neighboring distribution caused by RWP [104], and especially near the center of the simulation area. RD adopts the same principle as in RW, where mobile nodes select a random direction, speed,



**FIGURE 5.** Trajectories of random-based mobility models. (a) RW. (b) RWP. (c) RD. (d) MG.

and distance. The nodes move towards the boundary and pause for a while, and then randomly select another direction to move. As depicted in Figure 5(c), the only difference from RW is that the nodes' distribution is uniform, regardless of their initial locations. RD model is tested in FANETs in [110].

MG (Manhattan Grid) [111] is a random-based mobility model using a grid road topology. MG is used to realistically emulate the movements of vehicles in urban environments. At the intersections, the mobile nodes select random directions, speeds across the streets according to the ranges defined beforehand (*c.f.*, Figure 5(d)). In such mobility models, UAVs can perform the same directions as vehicles on the ground to accomplish a given mission [112].

## B. TIME-BASED MOBILITY MODELS

The movements of UAVs in this category are defined based on different mathematical equations, the instant of time, and the previous directions and speeds. All these parameters are considered for the smooth update of movements and to avoid sudden and sharp changes of speed and direction.

BSA (Boundless Simulation Area) [113], [114] is a mobility model operating in a geographically limited area. This limitation leads to a non-uniform distribution of mobile nodes and takes part in showing events, such as the frequent contact of the same nodes belonging to the same edge. Moreover, the mobility of each node has a relationship between its previous and current direction causing a harmful effect. BSA tries to avoid the latter by converting the 2D rectangular simulation into a boundless torus-shaped one (*c.f.*, Figure 6(a)). For instance, when a node reaches a boundary of the area, instead of bouncing on the border, it will appear on the opposite border of the area. This model is not widely adopted in FANETs [115].

GM (Gauss-Markov) [116] is a time-based mobility model designed to avoid sudden changes of movement and to be adapted to different levels of randomness via one tuning parameter. As shown in Figure 6(b), initially, each mobile node has a given direction and speed. Then, its future movement is defined based on its previous direction and speed. Consequently, the influence of previous directions and speeds allows GM to remove sharp motion changes and stops. GM is applied between UAVs in several works [117]–[119].

E-GM (Enhanced Gauss-Markov) [120] is a mobility model dedicated exclusively for FANETs. The novelty here resides in computing the directions of UAVs. Moreover, E-GM includes a mechanism of border avoidance, allowing soft changes at the boundaries. Initially, a random speed and direction are assigned to each UAV extracted from a uniform distribution range of speeds [50, 60] m/s and directions  $[0^\circ, 90^\circ]$ , respectively (*see* Figure 6(c)). E-GM is applied in many FANET applications [121]–[123].

ST (Smooth Turn) [124] is designed to support FANET monitoring applications. ST allows to capture the trend of UAVs to make regular trajectories (*e.g.*, typical turns with a large radius or straight trajectory). The example of Figure 6(d) shows a UAV randomly selects a set of points along the line perpendicular to its moving direction and hovers in circles around these points for random times. This model has been used in many protocols and applications [125]–[127].

3WR (Three-Way Random) [128] is a Markov process in which each UAV makes a random selection between three states: (i) turn left, (ii) turn right, and (iii) straight ahead. 3WR allows each UAV to modify its direction, to improve coverage, and to avoid zones that have been recently visited. In the case when a UAV approaches a turning radius with respect to an edge, it then turns into the center of the area until it reaches a randomly chosen direction  $[-45^\circ, 45^\circ]$  from normal from the edge of the area. 3WR can be considered as a variant of ST in which the duration of direction changes is static (*c.f.*, Figure 6(e)).

## C. PATH-BASED MOBILITY MODELS

In this category, a predefined trajectory is calculated beforehand and loaded in each UAV that it is forced to follow it without making a random motion. At the end of this planned path, the UAV can randomly change direction and repeat the same process.

SRCM (Semi-Random Circular Movement) [129] limits UAVs to move around a unique fixed center with variable radiuses. After making a full turn, the UAV selects randomly another radius and move another time around the same fixed center (*c.f.*, Figure 7(a)). SRCM is generally used in search and rescue applications, where UAVs move around a potential location and they are dispatched to gather

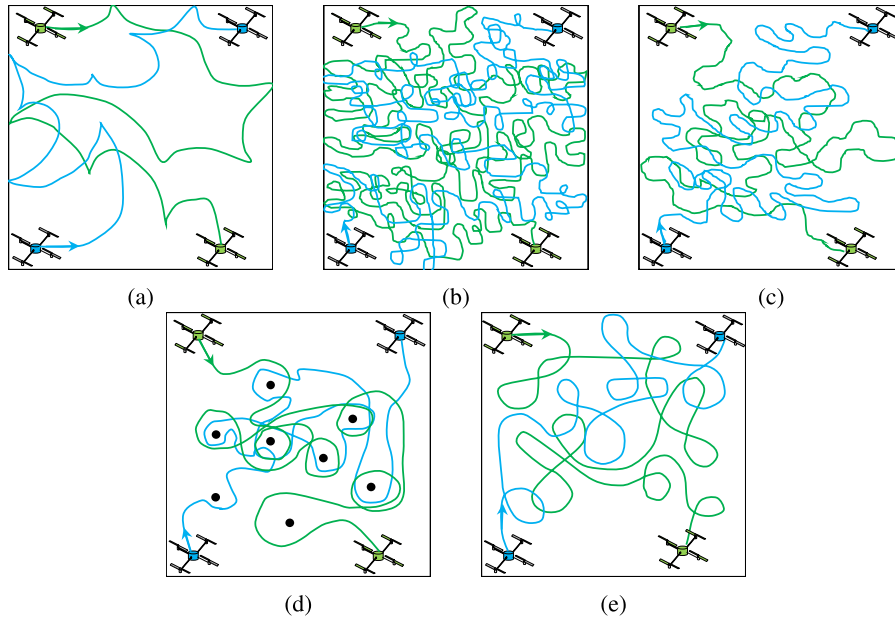


FIGURE 6. Trajectories of time-based mobility models. (a) BSA. (b) GM. (c) E-GM. (d) ST. (e) 3WR.

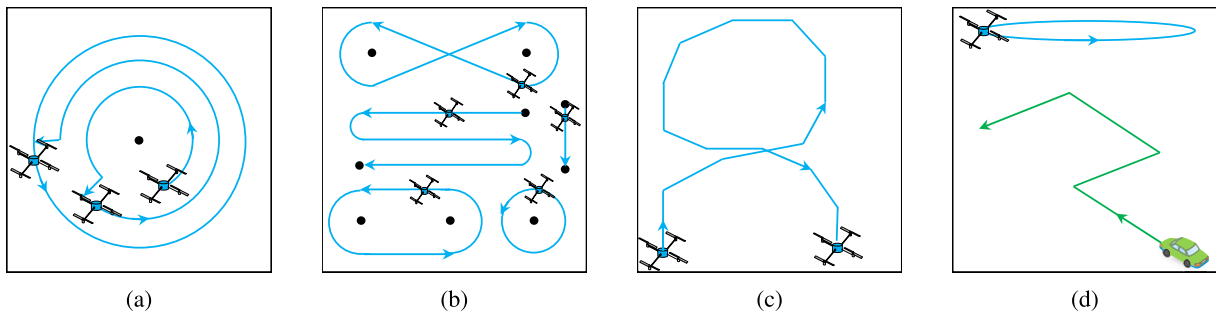


FIGURE 7. Trajectories of path-based mobility models. (a) SRCM. (b) PPRZM. (c) FP. (d) MT.

information in the nearby area. SRCM has been used in many works [130]–[132].

PPRZM (Paparazzi Mobility model) [133] is a path-based mobility model, adopting five possible motions: (i) Eight, (ii) Stay-At, (iii) Scan, (iv) Oval, and (v) Waypoint (*c.f.*, Figure 7(b)). In PPRZM, each possible movement that a UAV can make represents a state machine. This model has been used in many FANET protocols [134], [135].

FP (Flight Plan mobility model) [136] defines a flight plan in a mobility file, which is used to create a Time-Dependent Network Topology (TDNT) map (*c.f.*, Figure 7(c)). The latter is updated when the current flight plan deviates from the initial flight plan. FP is usually used for aerial transportation purposes where the full trajectory is planned beforehand. It has been adopted in particular in [137], [138].

MT (Multi-Tier mobility model) [139] allows to support multiple mobility patterns since FANETS can operate in heterogeneous networks (*e.g.*, airspace and ground networks). MT is a hybrid mobility model where at least two different

kinds of movements can be adopted for different kinds of nodes (*c.f.*, Figure 7(d)). MT is used in [140], [141].

#### D. GROUP-BASED MOBILITY MODELS

Generally, to accomplish a mission involving FANETS in a timely manner, UAVs tend to move together within a defined zone indicated by a reference point. This introduces spatial and temporal dependencies between UAVs.

ECR (Exponential Correlated Random) [128] is a group-based mobility model defining the movement of a group of mobile nodes in a correlated manner. To control the group, ECR uses a motion function to model all its possible movements. This is done by predicting the new locations of the group in the next time slot (*c.f.*, Figure 8(a)). ECR can be applied to FANETS to manage the movement as well as the collision avoidance of a set of UAVs.

NC (Nomadic Community) [142] is based on an invisible reference mobile node (*i.e.*, its movements and locations)

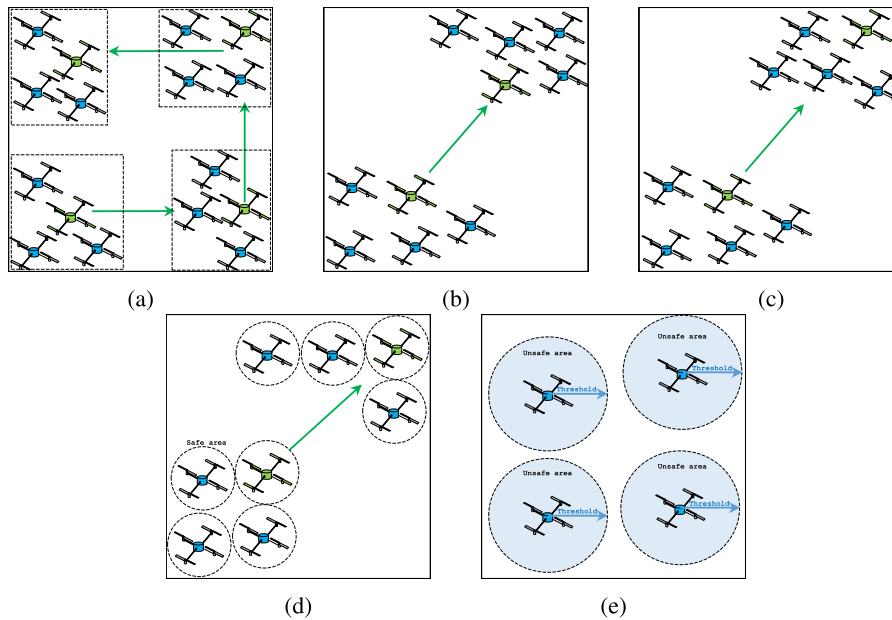


FIGURE 8. Trajectories of group-based mobility models. (a) ECR. (b) NC. (c) PRS. (d) PSMM. (e) STGM.

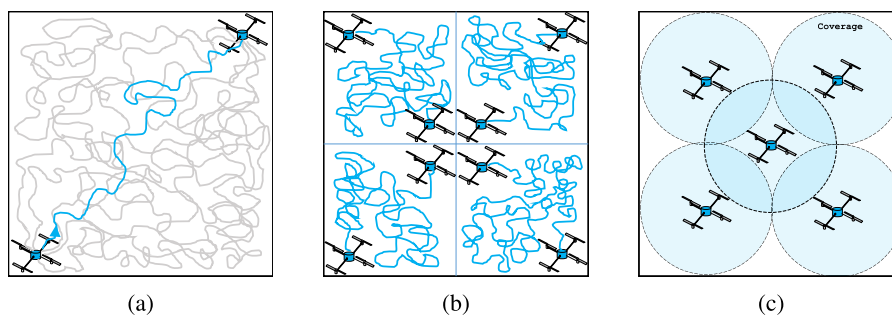


FIGURE 9. Trajectories of topology-based mobility models. (a) DPR. (b) H3MP. (c) SDPC.

to move a group of nodes. Within the group, the mobile nodes move randomly according to a random mobility model. Figure 8(b) shows the inflexible movements of mobile nodes as the group roams from one location to another. This kind of mobility models can be easily adapted for agricultural and military situations.

PRS (Purse Mobility Model) [142] is based on a different mechanism used by NC. In PRS, the group of mobile nodes moves together to catch a particular target. As illustrated in Figure 8(c), a single update equation combining an acceleration function and a random vector is used to calculate the future position of the mobile node. The random behavior of each mobile node is restricted in order to maintain efficient tracking of the target being pursued. PRS can be used when a group of UAVs tracks a suspect vehicle moving in an urban area.

PSMM (Particle Swarm Mobility Model) [143] uses a reference point to calculate the positions of UAVs. PSMM can calculate the future speed and direction of each UAV based on its previous ones (c.f., Figure 8(d)).

STGM (Spatiotemporally Correlated Group Mobility Model) [110] is a group mobility model using Gauss Markov model. STGM is based on both the spatial correlation and the temporal property of the trajectory of UAVs that are operating in a cooperative manner (c.f., Figure 8(e)).

### E. TOPOLOGY-BASED MOBILITY MODELS

When an application or network constraints need to be permanently satisfied across the time, a real-time control of UAVs' mobility is required. To do so, UAVs are supposed to be aware of their own topology by coordinating their locations between each other. For instance, when the connectivity of a network needs to be perpetually maintained, the movements of UAVs should be continuously controlled while avoiding useless random motions.

DPR (Distributed Pheromone Repel) [128] is a mobility model dedicated for FANETs and it uses pheromones and localized search to guide UAVs to the zones not recently visited by other UAVs. A flying UAV deposits virtual pheromones that disappear over the time on the

TABLE 5. Comparative study of FANET mobility models.

			Randomness	Collision avoidance	Connectivity	Deployment	Application	Main idea
Random	RW	Ref. [100]	√	×	×	2D area	Random flight	Randomly selects direction, speed, and distance.
	RWP	Ref. [104]	√	×	×	2D area	Patrolling	Waits a pause time before each random direction.
	RD	Ref. [108]	√	×	×	2D area	Reconnaissance	Enhances the distribution of mobile nodes comparing to RWP.
	MG	Ref. [111]	√	×	×	2D area	Traffic monitoring	Emulates the movements of vehicles in urban city.
Time	BSA	Ref. [113]	×	×	×	3D area	Random search	Converts the rectangular simulation into a boundless torus.
	GM	Ref. [116]	×	×	×	3D area	unpredictable mission	Defines the future movements based on the previous ones.
	E-GM	Ref. [120]	×	×	×	3D area	Rescue operations	Avoids borders and softly changes at the boundaries.
	ST	Ref. [124]	√	×	×	3D area	Hovering on a target	Randomly selects both a set of points and a turn radius.
	3WR	Ref. [128]	√	×	×	3D area	Reconnaissance	Makes a state random selection using a probability.
Path	SRCM	Ref. [129]	√	√	×	2D area	Scanning an area	Moves around a fixed center with a random radius.
	PPRZM	Ref. [133]	×	×	×	2D area	Specified mission	Represents five possible movements based on a state machine.
	FP	Ref. [136]	×	√	×	3D area	Transportation	Initially defines the flight plan that can be updated.
	MT	Ref. [139]	√	×	×	3D area	UAV-to-VANET	supports multiple mobility patterns at the same time.
Group	ECR	Ref. [128]	√	×	√	3D area	cooperative missions	Models the movements based a motion function.
	NC	Ref. [142]	√	×	×	3D area	Network coverage	Moves the group of nodes based on an invisible reference node.
	PRS	Ref. [142]	×	√	×	3D area	Agricultural scenario	Moves the group in order to catch a given target.
	PSMM	Ref. [143]	√	√	×	3D area	Platoon	Calculates the direction of nodes using a reference point.
	STGM	Ref. [110]	√	√	×	3D area	Surveillance	Considers temporal property of UAV trajectory and correlation.
Topo.	DPR	Ref. [128]	√	×	×	3D area	Real-time missions	Uses pheromones to define the movements of nodes.
	H3MP	Ref. [144]	√	×	×	3D area	reaching victims	Combines Markov model and DPR to estimate the movements.
	SDPC	Ref. [145]	√	√	√	2D area	connectivity recovery	Enhances the coverage of ground networks based on positions.

zone it has visited. Each UAV periodically shares the area pheromone map that is merged with other pheromone maps of other UAVs. In the case when a UAV finds a pheromone in its neighborhood, it selects its next direction based on a probability defined beforehand (*c.f.*, Figure 9(a)). This model can be used in different search and rescue applications using UAVs.

H3MP (Hybrid Markov Mobility Model with Pheromones) [144] is a combination of DPR and Markov models exploiting the advantages of both in a specified area decomposed of zones. Markov model enhances the overall movement of UAVs using their previous locations in the inter-zone. While the pheromone mechanism permits to control the mobility of UAVs by sharing information among UAVs within the zones (*c.f.*, Figure 9(b)). This model can be applied in multiple disaster areas.

SDPC (Self-Deployable Point Coverage) [145] is a topology-based mobility model dedicated to FANETS. SDPC can be applied to enhance the coverage of a maximum of mobile nodes located on the ground while maintaining connectivity among UAVs. To do so, an optimal positioning of UAVs has to be considered to cover the largest possible area (*c.f.*, Figure 9(c)). As an application of this model, SDPC can deploy UAVs over a disaster area in order to create substitution infrastructures that the affected people can use.

To have a more straightforward overview, TABLE 5 provides a summary of all described FANET mobility models including their main ideas, their potential FANET applications, and the categories that they belong to. A comparison between the main features that are considered as the key components differentiating between the mobility models,

such as the randomness that defines the degree of random motion used in each mobility model, the collision avoidance, the connectivity that is defined as the distance separating the UAVs, and the deployment area.

#### IV. ROUTING TECHNIQUES

Several routing techniques have been designed to accommodate to the various constraints that can arise at any time in FANETS [146]. Moreover, since many mobility models can be adopted for the movement of UAVs, the relays' selection methods are diversified aiming for decreasing the packet losses and to enhance the performances [147]. Each technique can only be used in a specific situation of the network or in the case when a given event has occurred. In this section, we describe twelve techniques that are the most commonly used in FANETS along with their limitations and drawbacks. In addition, we provide twelve explanatory figures showing a concrete example of each routing technique (*see* Figure 10). Finally, a brief comparative study between the discussed routing techniques is provided in TABLE 6.

##### A. STORE-CARRY AND FORWARD (SCF)

When the network suffers from intermittent connectivity, the custodian continues to carry the packets until encountering another node or the corresponding destination. As shown in Figure 10(a), UAV *D* is not in range of the custodian UAV *C* that continues to carry the packet during certain time  $\Delta t$  ( $\Delta t = t_2 - t_1$ ) until meeting UAV *D* where the data packet is forwarded. As a limitation, this technique introduces

**TABLE 6. Comparative study of FANET routing techniques.**

	GPS	Hello packets	Discovery packets	Buffering of packets	Destination's position	Motion information	Node election	Residual energy	Advantage	Drawback
SCF	√	√	×	√	√	Neighbors	Sometimes	Sometimes	Overcomes network fragmentation.	Introduces high delivery delays.
GF	√	√	×	×	√	Neighbors	Yes	No	Reduces delay of transmission and number of hops.	Fails at local optimums.
PR	√	√	×	×	√	Neighbors	Yes	Sometimes	Reduces link disconnections.	Requires highly dense networks.
DP	√	√	√	×	×	Sometimes	No	Sometimes	Has an accurate vision about routing paths.	Introduces an important overhead.
CL	√	√	×	×	√	Sometimes	Yes	Sometimes	Organizes the network into different connected groups.	Does not support poorly dense networks.
LST	√	√	√	×	×	Sometimes	No	Sometimes	Shows an accurate vision of the network topology.	Introduces a large amount of overhead.
HR	√	√	×	×	×	Sometimes	Yes	Sometimes	Defines routing paths to all nodes.	Does not support high mobility of nodes.
MI	√	√	×	√	√	All nodes	Yes	Sometimes	Improves the network connectivity.	Does not support severely fragmented networks.
EE	√	√	√	×	√	Sometimes	Yes	Yes	Regulates the energy consumption among nodes.	Generally, does not consider connectivity.
STA	×	×	×	×	√	No	No	No	Improves delivery ratio of packets.	Does not support topology variations.
SC	√	√	√	√	√	All nodes	Yes	Sometimes	Selects honest nodes for data delivery.	Requires complex calculations.
BR	√	√	√	×	×	No	No	No	Ensures successful data transmission.	Introduces a large amount of overhead.

a high delay, and therefore it is not appropriate for real-time applications.

**B. GREEDY FORWARDING (GF)**

The aim of this technique is to decrease the number of transited relays in which a packet can traverse during a single communication. Each packet is forwarded to a neighbor UAV that is geographically closest to its destination. As depicted in Figure 10(b), the current UAV *C* selects UAV *F*<sub>1</sub> instead of UAV *F*<sub>2</sub> as a next hop to deliver the data packet until UAV *D*, since it is the closest one to UAV *D* ( $D_1 < D_2$ ). As a drawback, this process can fail a local optimum, which can be recovered using many techniques.

**C. PREDICTION (PR)**

Sometimes it is required to know the future positions of the next relays using their speeds and directions in order to select the adequate one. For instance, UAV *S* selects UAV *F*<sub>1</sub> as a next hop since its future position is getting closer to the destination (see Figure 10(c)). This technique requires additional information about the destination and the neighbors.

**D. DISCOVERY PROCESS (DP)**

Due to its simplicity, the flooding technique is often used in highly dynamic networks, such as FANETs, and especially when the destination's location is not known. In a general case, route request (RREQ) is disseminated to find all

possible paths towards the destination UAV *D*. At the end, UAV *D* makes a routing decision by selecting the appropriate path for the data delivery (c.f., Figure 10(d)). As a drawback, although the packets will reach their destinations, this can cause significant congestion and bandwidth consumption.

**E. CLUSTERING (CL)**

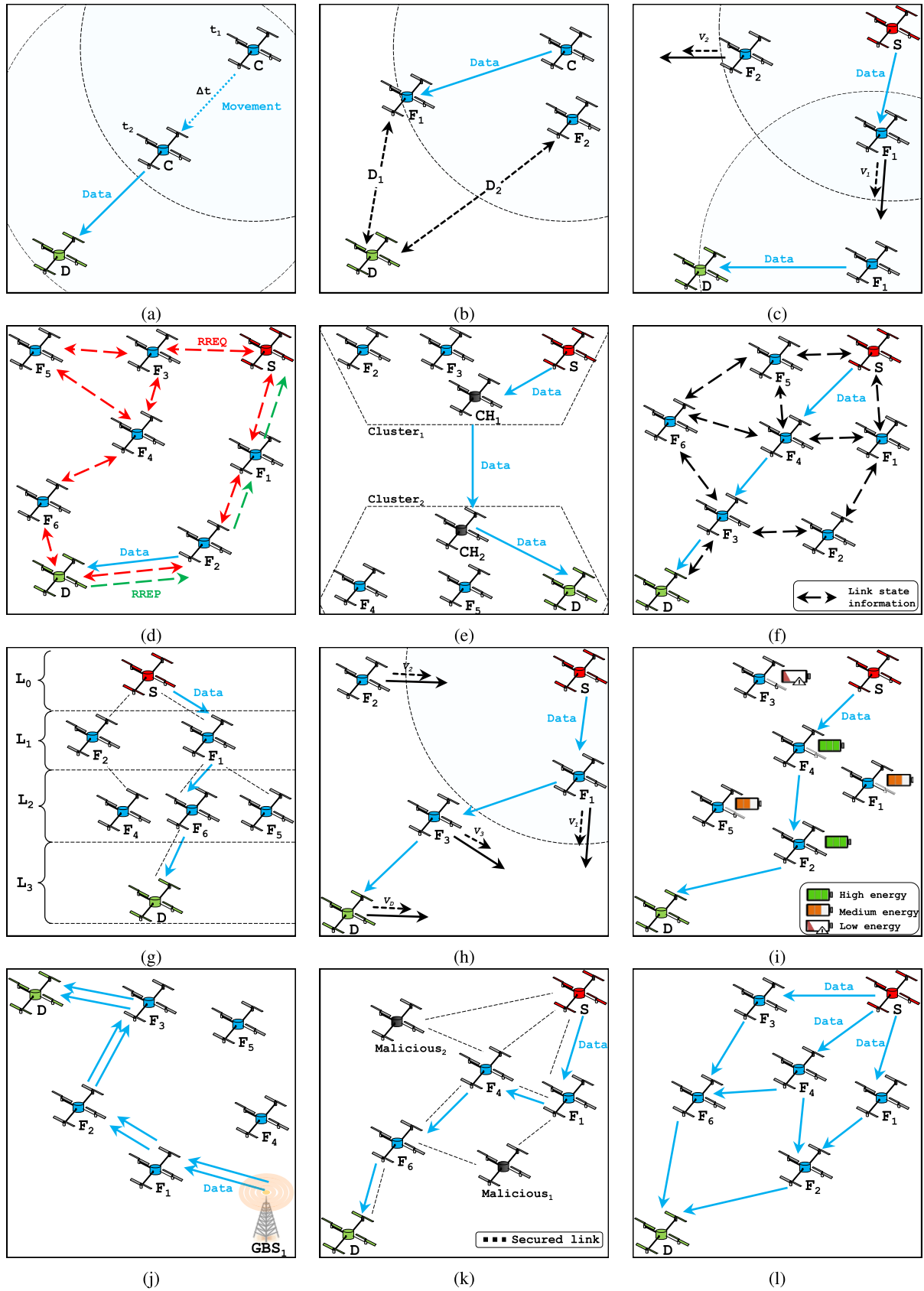
When a FANET is highly dense, it is preferably organized in the form of zones (clusters) where each one is controlled by a cluster-head, respectively. When UAV *S* belonging to *Cluster*<sub>1</sub> wants to establish a communication with UAV *D* belonging to *Cluster*<sub>2</sub>, the transmission has to be transited through their respective cluster-heads (c.f., Figure 10(e)). However, it causes an important overhead to form such clusters.

**F. LINK STATE (LST)**

In each topology variation, link state information about the whole network has to be shared between all UAVs. This allows each UAV to both have an accurate vision about the network and calculate the shortest path between the communicating UAVs (see Figure 10(f)). Nevertheless, a large amount of overhead is distinguished in such a technique.

**G. HIERARCHICAL (HR)**

This technique consists to divide the network into several levels in the form of trees. Each level is controlled by at least



**FIGURE 10.** FANET routing techniques. (a) Store-Carry and Forward. (b) Greedy Forwarding. (c) Prediction. (d) Discovery Process. (e) Clustering. (f) Link State. (g) Hierarchical. (h) Mobility Information. (i) Energy-Efficient. (j) Static. (k) Secure. (l) Broadcast.

a root UAV that is responsible to communicate with the upper and lower levels (*c.f.*, Figure 10(g)). However, low mobility is required for this kind of technique.

#### H. MOBILITY INFORMATION (MI)

The motion information, such as positions, velocities, and speeds are all used to select at each time the next relays (*c.f.*, Figure 10(h)). Moreover, this technique also allows to know the motion information of all nodes in the network. However, a high exchange of Hello packets is required.

#### I. ENERGY-EFFICIENT (EE)

To increase the lifetime of FANETs, the energy consumption among UAVs has to be well-balanced by sparing UAVs having low residual energy from any participation during the data communication between UAV *S* and UAV *D* (*c.f.* Figure 10(i)). However, other connectivity techniques need to be combined to avoid packet losses.

#### J. STATIC (STA)

As shown in Figure 10(j), the routing tables of the communicating UAVs are filled beforehand and the same routing path is always used for the data transmission. However, this technique does not support the variation of the topology.

#### K. SECURE (SC)

As depicted in Figure 10(k), different security mechanisms are used to secure all existing links in the network, to detect any malicious UAV, and avoid it during the data transmission while transiting only the honest UAVs. However, complex processing and calculations are carried out by UAVs.

#### L. BROADCAST (BR)

To ensure a successful data transmission, the data packet is disseminated across the network from the source UAV *S* to the destination UAV *D* (*see* Figure 10(l)). However, BR can introduce a significant overhead on the network and provoke congestion in the case of a broadcast storm problem.

### V. FANET ROUTING PROTOCOLS

The conception of the network layer of FANETs constitutes one of the most serious challenges [148]. This creates an increased competition between researchers to conceive or to adapt different kinds of routing protocols while satisfying conflicting design constraints, such as the highly dynamic topology [149], the balanced energy consumption [77], the link breakage recovery [150], the scalability [151], the security [152], and the wise use of both UAV resources and allocated bandwidth [153]. However, fulfilling all these aforementioned constraints at once is quasi-impossible, thus diversifying the categories of FANET routing protocols according to the situation of the network. As depicted in Figure 11, FANET routing protocols can be categorized into eight categories based on the adopted technique and the issues to be addressed. In the subsequent sections, we study in detail each category along with its most relevant routing protocols.

#### A. TOPOLOGY-BASED ROUTING PROTOCOLS

Several of routing protocols belonging to this category are initially proposed for MANETs and they are updated in order to be adapted to the unique characteristics of FANETs [154]. These protocols are based on the information of links by exploiting IP addresses of mobile nodes to exchange packet between the communicating nodes. This category is further categorized into four categories: (i) Proactive, (ii) Reactive, (iii) Hybrid, and (iv) static.

##### 1) PROACTIVE

This category stores information related to all fresh links between each pair of mobile nodes in the routing tables. These tables are shared at each change of the topology. Consequently, it is simple to pick out the shortest routing path between a source and destination, thus reducing significantly the delivery delay. Nevertheless, since the topology of FANETs is highly dynamic, proactive protocols exchange a lot of packets, thus consuming bandwidth, congesting the network, and slowly reacting to disconnections. For this reason, proactive protocols can be suitable if, and only if, some crucial updates are adopted.

OLSR (Optimized Link State Routing Protocol) [155] has been addressed in several recent studies [156]–[162], which have applied OLSR in FANETs under different simulation environments. OLSR is based on a link state routing strategy in order to establish a global knowledge of all existing links between UAVs. This is done using the periodical exchange of Hello and Topology Control (TC) packets between the UAVs so as to refresh the topology information of the network. OLSR selects MultiPoint Relay (MPR) UAVs to cover two-hop neighbors, to generate link state information, and to forward data packets to other MPRs, thus reducing the overhead. In the example shown in Figure 12(a), when a source UAV *S* wants to engage a communication with a destination UAV *D*, it selects an MPR as an intermediary to relay the data packets to *D*. Moreover, MPRs periodically share to the network their accessibility state to all UAVs.

D-OLSR (Directional Optimized Link State Routing Protocol) [163] is an extension of OLSR, where UAVs are equipped with directional antennas to enhance the transmission range. To further minimize the overhead, the number of MPR UAVs is reduced significantly. Indeed, the source UAV estimates the distance to the destination UAV. If for instance, the distance is greater than  $D_{max}/2$  (*i.e.*,  $D_{max}$  is the range provided by a directional antenna), the farthest UAV is selected as an MPR. Otherwise, the classical OLSR is executed to select the MPR UAVs. In the scenario depicted in Figure 12(b), D-OLSR tends to reduce the number of MPRs by selecting only the farthest ones, thus minimizing the overhead. However, in the case where the distance is smaller than  $D_{max}/2$ , D-OLSR will switch to the classical OLSR.

ML-OLSR (Mobile and Load-aware Optimized Link State Routing Protocol) [164] is proposed in order to avoid selecting high-speed UAVs as MPRs. The geographical positions



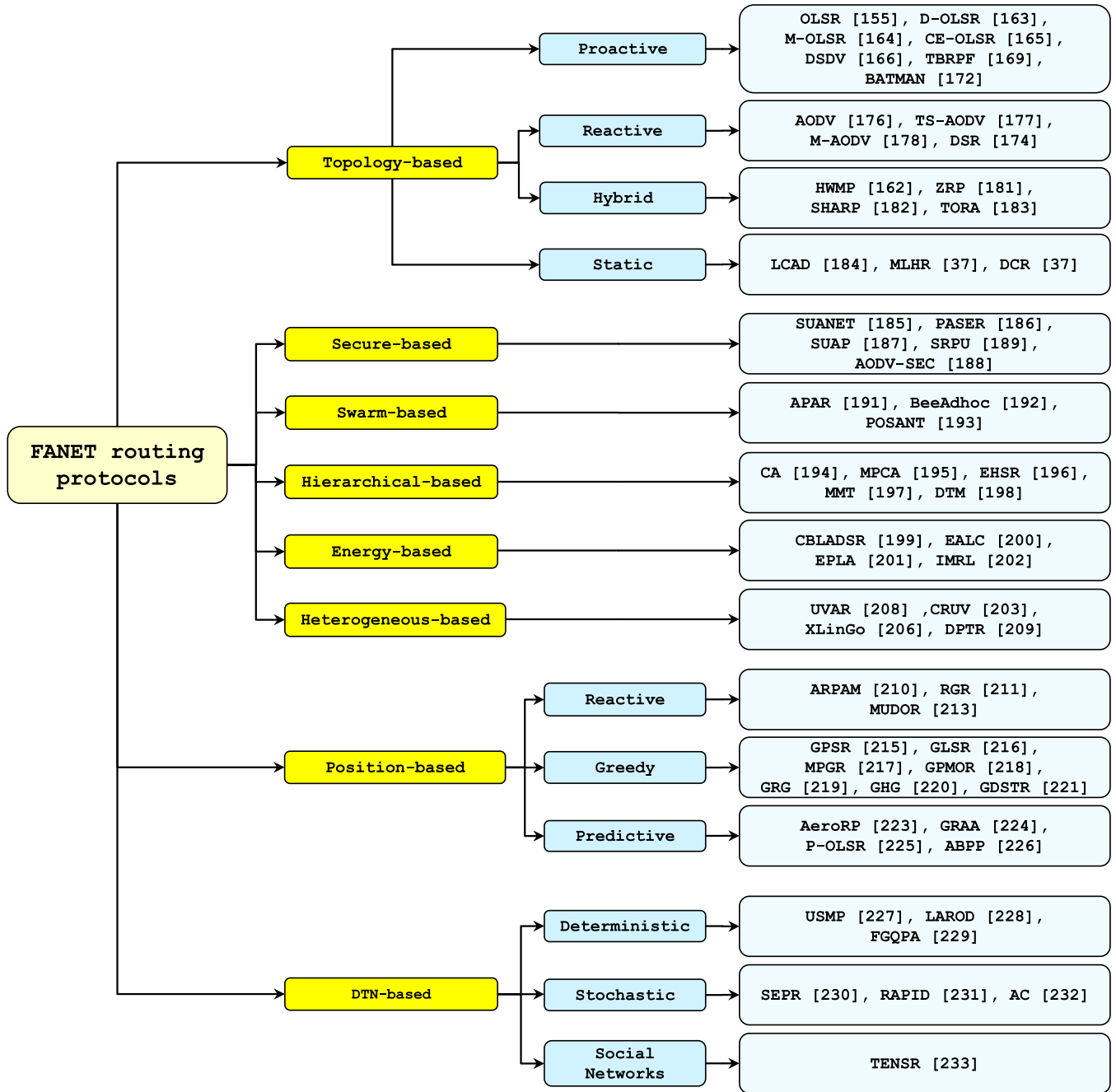
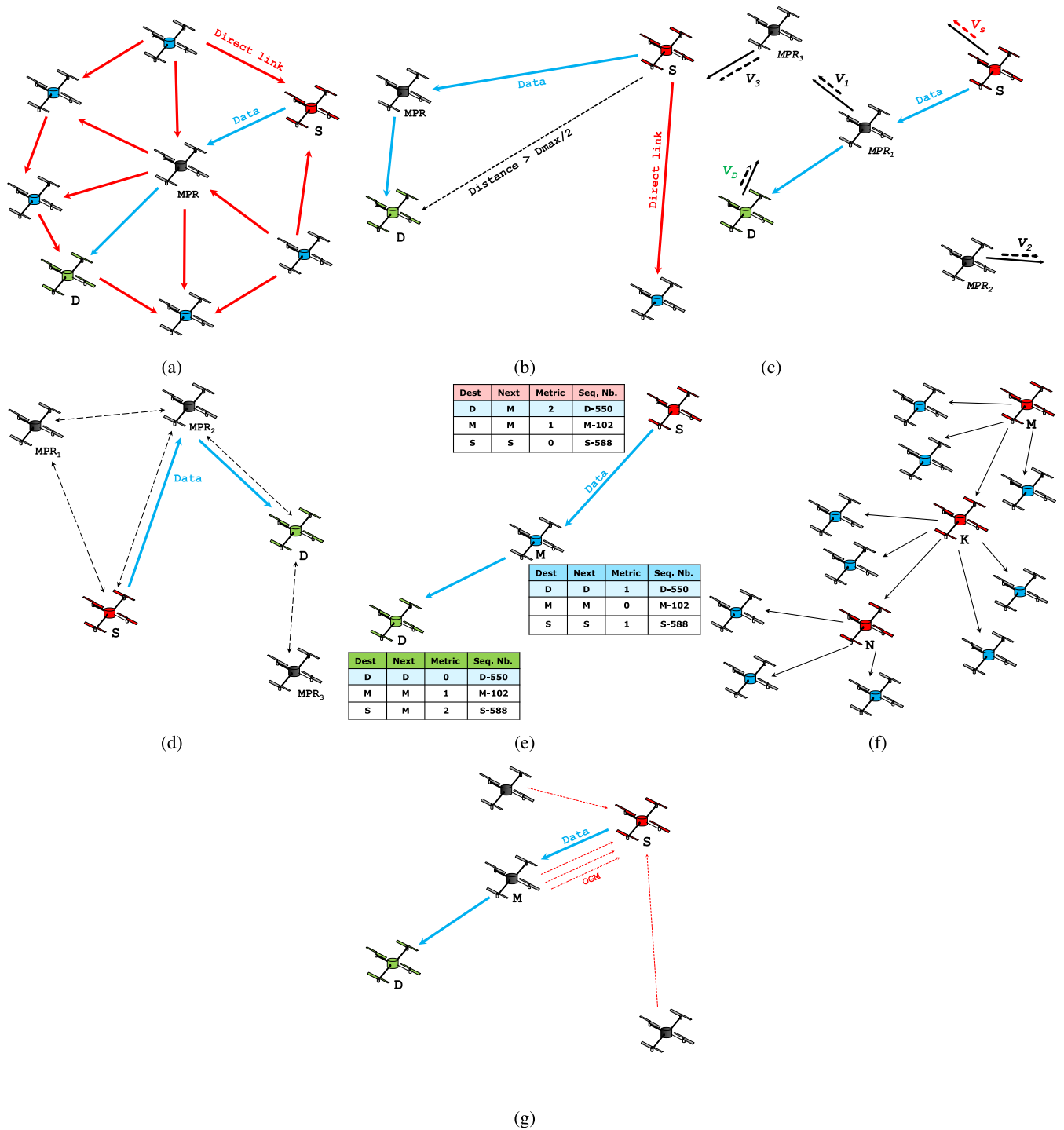


FIGURE 11. Taxonomy of FANET routing protocols.

and speeds between the neighbors are considered in ML-OLSR. Indeed, two metrics are calculated before each selection of MPR, which are called the Stability Degree of Node (SDN) and the Reachability Degree of Node (RDN). SDN depicts the stability of the communication link between UAVs where those close to each other are selected to be MPRs. As for RDN, it avoids collision and interference between the neighboring UAVs, and thus enhancing the packet delivery ratio and the data delivery delay. These two metrics are included in the Hello packets and shared

periodically with UAVs in range in order to be aware of the distance, the mobility, and the load information of neighboring UAVs. The selection of MPRs is carried out based on SDN of each neighboring UAV. The selected MPRs are considered to be likely staying in range during a long period of time to relay data packets between the pairs of source and destination UAVs. In the example shown in Figure 12(c), UAV *S* selects the most stable link among the existing links for each UAV (i.e.,  $MPR_1$  in Figure 12(c)). Consequently, this can reduce the link failures and avoid the re-selection process of MPRs.



**FIGURE 12.** Proactive routing protocols. (a) MPR selection in OLSR. (b) Mechanism of D-OLSR. (c) Mechanism of ML-OLSR. (d) Mechanism of CE-OLSR. (e) Mechanism of DSDV. (f) Mechanism of TBRPF. (g) Mechanism of BATMAN.

CE-OLSR (Cartography Enhanced Optimized Link State Routing Protocol) [165] is an enhanced version of the well-known OLSR [155] to take into account the high mobility in highly dynamic networks, such as FANETs. As its name suggested, CE-OLSR is based on the network cartography rather than the network topology. Two main concepts are

used in CE-OLSR: (i) cartography gathering scheme and (ii) stability routing scheme. The first concept tries to improve the tracking of node mobility in order to build a much accurate network topology. Based on the signaling of OLSR, the network cartography is gathered. To do so, the positions of the nodes as well as their neighbors are included both

in Hello and TC packets before sharing them. The routing path stability is based on the second concept by calculating a *Stability Distance* metric. The latter is the distance separating two nodes, which should be less than another small communication range. In the scenario illustrated in Figure 12(d),  $MPR_1$  is an MPR of UAVs  $MPR_2$  and  $S$ ,  $MPR_2$  is an MPR of UAVs  $S$  and  $D$ , and  $MPR_3$  is an MPR of UAV  $D$ . The TC generated by  $MPR_2$  (i.e.,  $TC_B$  advertising UAVs  $S$  and  $D$ ) declares to  $MPR_1$  a new link between UAVs  $MPR_2$  and  $D$  (i.e.,  $MPR_2 \leftrightarrow D$ ). That way, the remaining network (i.e., UAVs farther than 2-hops away) is discovered via TC messages. To send a data packet from UAV  $S$  to UAV  $D$ , CE-OLSR simply uses the Dijkstra algorithm to calculate the shortest path, which is also used to calculate the different routing tables of all UAVs belonging to the network.

DSDV (Destination-Sequenced Distance Vector) [166] is a table-driven routing protocol based exclusively on the Bellman-Ford algorithm. Two kinds of metrics are used both to avoid routing loops and to refresh local information of any topology variation. The first metric is the sequence numbers that are updated to define the freshness of the links, while the second metric is the incremental dumping parameters (i.e., all routing table information), which are included in the packets and broadcasted whenever the topology of the network changes. DSDV is adopted in several works, such as in [22], [160], [167], [168]. In the example depicted in Figure 12(e), each UAV maintains a routing table and updates it periodically about the complete network. As the topology changes frequently, DSDV adds sequence numbers to interpret the freshest routing path (i.e., the recently used path with the highest sequence number is preferred over a path with a lower sequence number).

TBRPF (Topology Broadcast based on Reverse-Path Forwarding) [169] is a proactive-based routing protocol exploiting the shortest paths provided by the Dijkstra's algorithm, and thus delivering data packets across the network. In TBRPF, each node calculates a source tree using partial topology information recorded in its topology table. Thus, the source tree of each node includes the link state information to all reachable nodes. The broadcast mechanism and the periodical exchange of Hello messages are exploited by each node to keep all its neighbors up-to-date of their source tree. In [170], it is demonstrated that TBRPF can provide less overhead in FANET compared with OLSR [155]. Moreover, in [171], TBRPF has been adopted in a series of tests in FANETS where the link quality of each path and the minimum number of hops are considered. To have a global knowledge of the network, the UAVs  $M$ ,  $K$ ,  $N$  establish a path (i.e., a source tree) to all reachable UAVs in the network (see Figure 12(f)). Each UAV reports only the source tree part with their direct neighbors at each change in their status based on Hello packets. If UAV  $M$  disseminates an update, it will be relayed only by UAVs  $K$  and  $N$  to the rest of the network.

BATMAN (Better Approach To Mobile Adhoc Networking) [172] is a proactive routing protocol proposed to handle large size networks while using low traffic cost

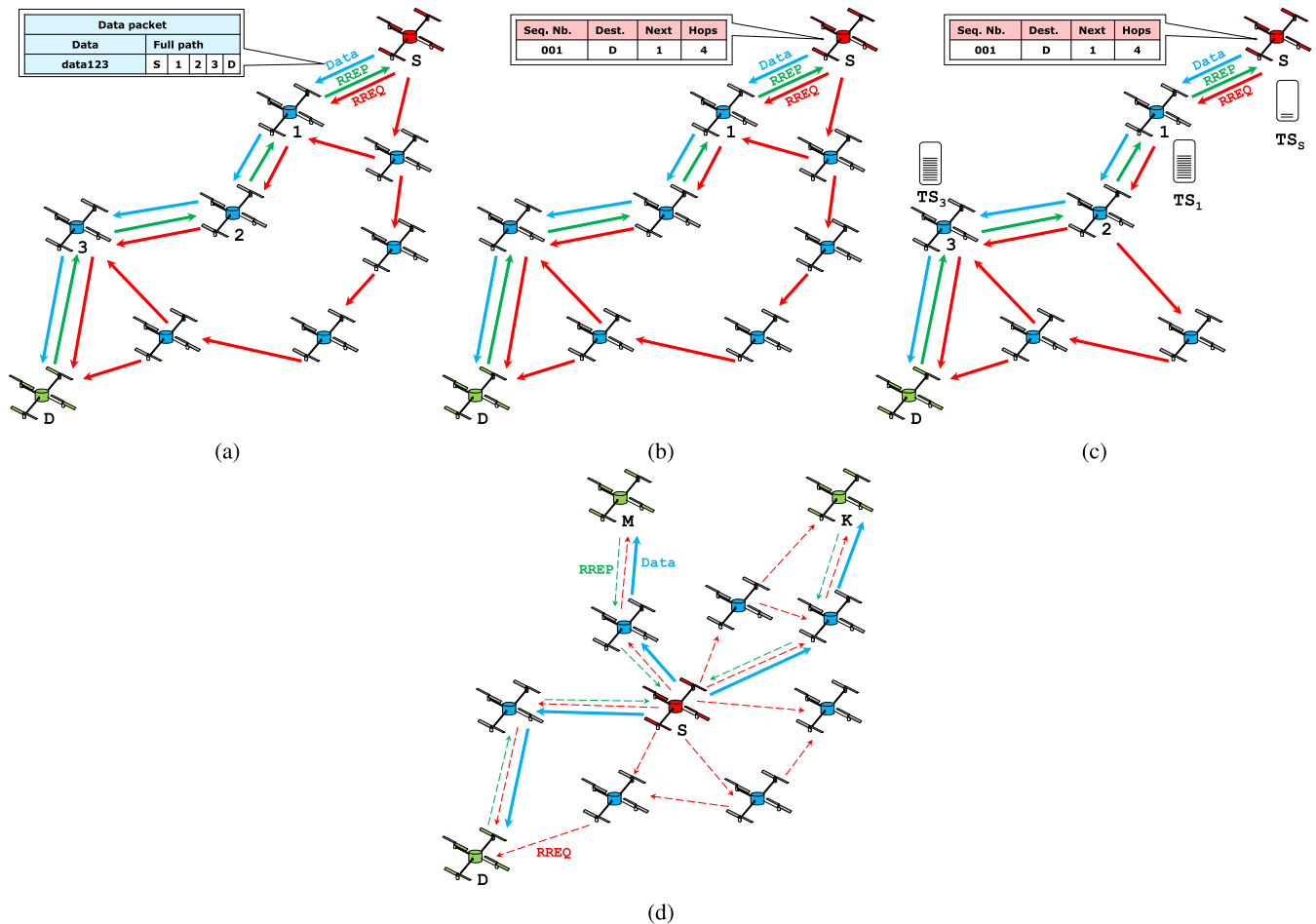
and processing. BATMAN maintains information of the direct neighbors accessible through a single hop by exchanging control packets called OriGinator Message (OGM). Only the link proving the best routing path towards all other nodes is maintained by each node using OGM. During each data transmission, a source node calculates the number of the received OGM from its neighbors and it selects as a next hop towards the destination node the one that had a fresh sequence number and sent more regularly the OGM. BATMAN has been applied to FANET in [173]. In the scenario of Figure 12(g), UAV  $S$  intercepts a certain number of the OGM allowing it to select the next hop towards UAV  $D$ . UAV  $M$  is selected as the next hop which will relay the data packet until that it reaches UAV  $D$ .

## 2) REACTIVE

Also named *On-Demand* routing protocols, a route discovery process is initiated only when a UAV wants to establish a communication, where the maximum of routing paths are explored, defined, and maintained. In the majority of cases, this category suffers from a high delay and latency time due to the discovery process, which also induces a significant overhead, particularly when the network is highly fragmented.

DSR (Dynamic Source Routing) [174] is a reactive routing protocol dedicated for MANETS. DSR allows the network to be self-organized and self-configured without relying on any infrastructures. Due to the reactive nature of DSR, a discovery process is deployed only when a communication is needed. In addition, a route maintenance mechanism is adopted to maintain any path failures. With its freedom of loop property, DSR provides the possibility to select multiple paths to any destination nodes. Each exchanged packet has to include all the addresses of the transited nodes making it inadequate for large networks and also for networks with a highly dynamic topology. DSR has been applied to FANETS in several works across the literature [22], [159], [175] where, in the majority of cases, it demonstrates its heaviness and its failure to face many disconnections. In the example of Figure 13(a), UAV  $S$  generates an RREQ packet, and broadcasts it over all UAVs constituting the network. As it progresses, the RREQ packet records in its header all the transited UAVs until the target UAV  $D$ . The routing decision is made based on the number of hops, where the shortest path is selected. Once a path is selected, the addresses of UAVs composing the path are included both in the route reply (RREP) and data packets in order to forward correctly the packets between UAVs.

AODV (Ad hoc On-demand Distance Vector) [176] is a combination of the DSR and DSDV protocols in which it inherits from them the hop-by-hop routing and the periodical updates of the routing tables, respectively. At each communication, AODV first initiates a discovery process to plot the routing path with the minimum number of hops. Unlike DSR, each exchanged packet includes only the destination address and the selected relay UAVs storing the nexthop corresponding to each data communication. This can minimize significantly the overhead and avoid network congestion.



**FIGURE 13.** Reactive routing protocols. (a) Mechanism of DSR. (b) Mechanism of AODV. (c) Mechanism of TS-AODV. (d) Mechanism of M-AODV.

To maintain the built paths, the freshness of the routes is increased based on the expiration time and the intermediate UAVs also updates their routing tables. There have been many attempts to adapt AODV in FANETs, such as in [160], [162]. Whenever UAV *S* wishes to communicate with UAV *D* it initiates a route discovery in order to trace the shortest (*i.e.*, fewer hops) routing path by disseminating RREQ packets over the network (*c.f.*, Figure 13(b)). Once a path is established by the destination (*i.e.*, sending an RREP packet unicastly), AODV transmits packets across the selected path without routing loops. A maintenance strategy is used to recover link failure issues. This strategy is based on a sequence number to find an updated routing path towards UAV *D*.

TS-AODV (Time-Slotted Ad hoc On-demand Distance Vector) [177] is a variant of the AODV protocol in which the time slotted principle is incorporated. To take control of the network congestion, and especially in the networks, such as FANETs (*i.e.*, a large number of UAVs), TS-AODV found a trade-off between the collision risk and the bandwidth consumption. Indeed, the control packets are sent during defined time slots, where only one node can make a data transmission. The duration of each time slot dedicated to each

kind of packets is estimated according to several factors, such as the size of the network, the link failure detection, and the topology changes. The functioning of TS-AODV is exemplified in Figure 13(c). As it is shown, the same mechanism of AODV is used to establish a routing between UAV *S* and UAV *D*. However, each transited UAV including *S* and *D* has to set a time slot  $TS$  for each transmitted packet in order to avoid collisions, reduce the bandwidth consumption, and thus increasing the packet delivery ratio.

M-AODV (Multicast Ad hoc On-demand Distance Vector) [178] is an improved version of AODV [176] to take into account the multicasting concept to connect a set of nodes. M-AODV can be easily adapted to FANETs by building multicast trees using a reactive strategy (*i.e.*, discovery process). The multicast tree is dynamically created as UAVs that act as routers join the group. When a link failure occurs, it is recovered by a downstream UAV flooding an RREQ packet. M-AODV not only provides a multicast routing, but also supports a unicast communication. In the scenario shown in Figure 13(d), when a multicast source *S* wants to share a data packet with several multicast receivers *M*, *K*, and *D*, a discovery process is initiated to get appropriate routing

paths towards each destination. An RREP packet is sent back to UAV  $S$  from each receiver to plot the different routing paths towards them, which will be then exploited to transmit each copy of the data packet.

### 3) HYBRID

To address the limitations of proactive and reactive protocols, hybrid protocols combine the benefits of both. Indeed, proactive and reactive protocols need an important overhead to maintain the whole network and a sufficient time to establish the best routes, respectively. As a classical solution, hybrid protocols adopt the concept of zones where the proactive strategy is deployed inside the zones, thus limiting the overhead. As for the inter-zone communication, the reactive strategy is used only between specific nodes belonging to the zones.

HWMP (Hybrid Wireless Mesh Protocol) [179] is a hybrid routing protocol dedicated to Wireless Mesh Networks (WMNs) and applied in FANETs, such as in [162], [180]. HWMP combines reactive and proactive strategies to select an on-demand routing path and proactively build tree. The reactive and proactive strategies are based on AODV protocol [176] and a classical distance vector protocol, which can be all used simultaneously. The reactive strategy allows a source UAV to establish a communication with a destination UAV. This strategy is used by UAVs when the topology is changing frequently, and especially when no root UAV exists. When the topology is not changing (*e.g.*, static), the proactive strategy is an efficient choice for UAVs. Four elements are used in HWMP: (i) Root ANNouncement (RANN), (ii) Path REQuest (PREQ), (iii) Path REPLY (PREP), and (iv) Path ERRor (PERR). Since HWMP is adopted in IEEE 802.11s at the MAC layer, the used routing metric is airtime cost that estimates the link quality (*e.g.*, the consummation of channel resource). When the topology changes frequently as in FANETs, a reactive strategy similar to AODV is used by flooding a PREQ over the network when a communication between UAV  $S$  and UAV  $D$  needs to be established (*c.f.*, Figure 14(a)). If the intercepted PREQ defines a new and better routing path towards UAV  $S$ , UAV  $D$  will respond with a PREP through the new path. If the intermediate UAVs do not have any routing path towards UAV  $D$ , the PREQ packet is just forwarded further.

ZRP (Zone Routing Protocol) [181] is a hybrid routing protocol combining two kinds of routing: (i) reactive and (ii) proactive. ZRP is based on the concept of zones, where each zone contains a set of nodes. Each zone is defined based on the distance separating the nodes using a predefined radius  $R$ . To communicate, the nodes belonging to the same zone use the concept of Intra-zone routing based on a proactive approach. Otherwise, the nodes use the concept of Inter-zone routing based on a reactive approach. ZRP has been applied and proven its effectiveness to FANETs in [22]. When UAV  $S$  and UAV  $D$  are in the same zone, UAV  $S$  can start immediately the data transmission. If UAV  $S$  has a data packet to be sent outside the zone, a discovery process has to

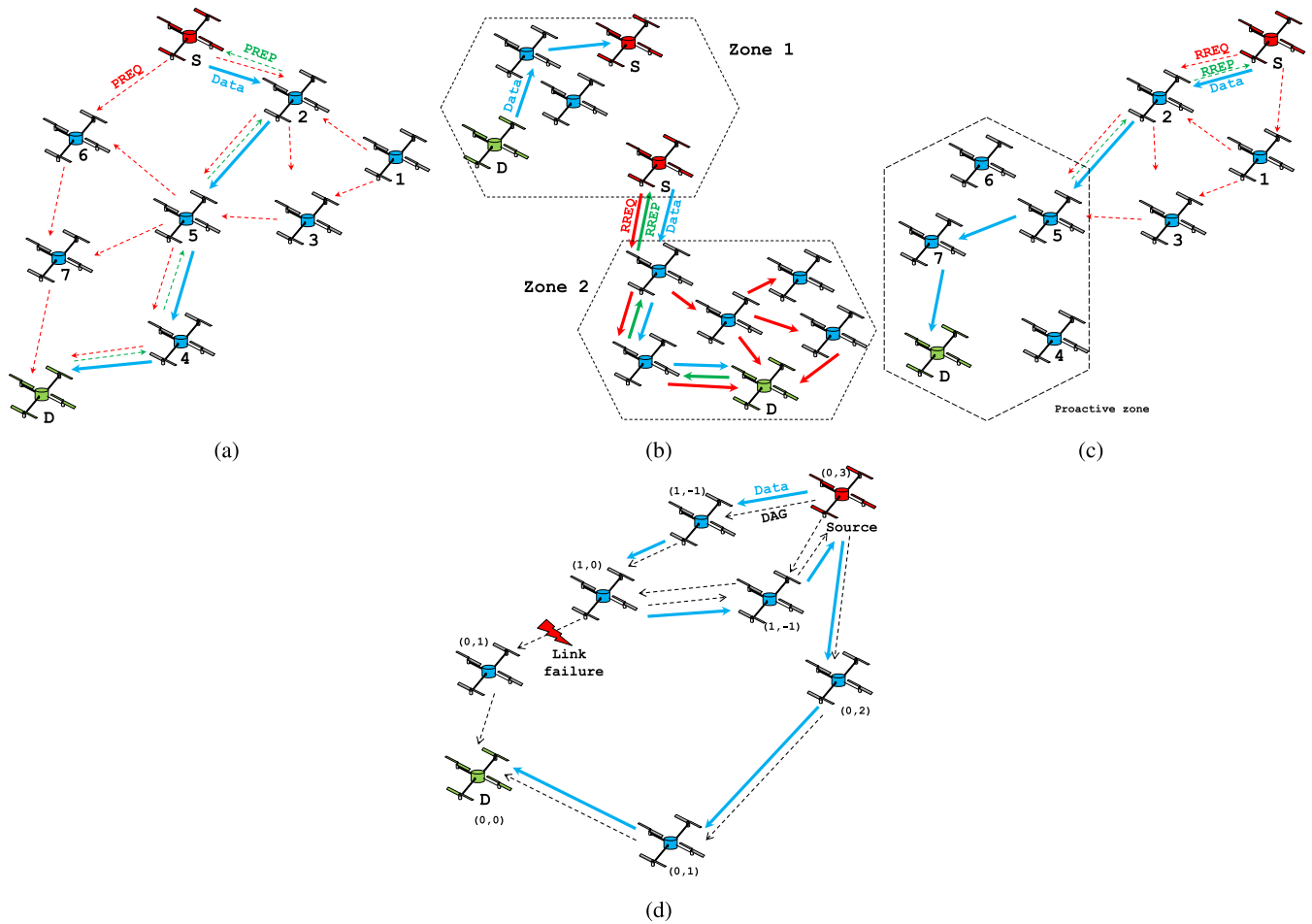
be applied to establish a routing path to the target destination (*c.f.*, Figure 14(b)).

SHARP (Sharp Hybrid Adaptive Routing Protocol) [182] tends to provide a trade-off between a proactive and reactive routing by dynamically changing the amount of routing control packets shared proactively. Proactive zones encompassing a set of UAVs are defined based on the distance (*i.e.*, number of hops) up to which the control packets should be shared. The reactive mechanism is used when the destination UAV is not present in the proactive zone. UAVs belonging to the same proactive zone maintain routes proactively. In SHARP, proactive zones act as collectors, *i.e.*, once the data packets reach any UAV belonging to the zone, it delivers the data packet correctly to the destination. In the example of Figure 14(c), UAV  $S$  tries to communicate with UAV  $D$  that is located in the proactive zone. UAV  $S$  initiates a discovery process towards the proactive zone, since it does not belong to this zone. Once the RREQ packet reaches any UAV belonging to the zone (*i.e.*, UAV 5), an RREP packet is sent back to UAV  $S$ . At the interception of the RREP packet, UAV  $S$  starts the data delivery towards the proactive zone in which UAV 5 can find immediately the route towards the destination.

TORA (Temporarily Ordered Routing Algorithm) [183] is a hybrid distributed routing mechanism, which is appropriate for highly dynamic networks like FANETs. TORA only updates and maintains communication links of the neighboring UAVs. The main aim of TORA is to reduce the exchange of control packets in the case of topology changes. TORA creates and maintains a Directed Acyclic Graph (DAG) between the communicating UAVs where several routes exist between them. Moreover, the longer routes are often adopted by TORA to minimize the overhead. As a conclusion, TORA uses both reactive and proactive mechanisms according to the situation of the network and it finds new routes in case of link failures. As depicted in Figure 14(d), each UAV has a unique metric value called Height in DAG. Initially, the Height value of UAV  $D$  is set to 0 while all other UAVs will see their heights initialized to NULL. UAV  $S$  broadcasts an RREQ packet including the identifier of UAV  $D$ . A UAV having a non-NULL height replies with an RREP packet including its height. The UAV that has intercepted the RREP packet increments its height relative to the UAV generating the RREP packet. Consequently, a DAG is created from UAV  $S$  to UAV  $D$ . In the case of link failure, the DAG should be re-established towards UAV  $D$  by generating a new reference level, thus resulting in its propagation by the neighboring UAVs. Therefore, the links are reversed to create a new route according to the new reference level.

### 4) STATIC

This category is appropriate for a network having a constant topology, which makes it inadequate for FANETs. To communicate, each routing table is calculated and filled beforehand and stored in each UAV. It should be stressed that the routing tables cannot be updated, which allows UAVs to communicate only with a few UAVs or base stations located



**FIGURE 14. Hybrid routing protocols. (a) Mechanism of HWMP. (b) Mechanism of ZRP. (c) Mechanism of SHARP. (d) Mechanism of TORA.**

on the ground. In the case of link failures, static protocols are not able to function normally, thus disturbing the whole network.

MLHR (Multi-Level Hierarchical Routing) [37] is a static routing protocol designed to handle the scalability issue of the network. To do so, FANETs are organized in the form of clusters, where each cluster has a cluster-head (CH) representing the whole cluster. Each CH has different connections outside the cluster (*i.e.*, ground stations, UAVs, airplanes, copters, *etc.*) and inside with direct communication range UAVs. This kind of routing can be suitable for FANETs if the mobility of UAVs are pre-defined based on swarms or an important number of UAVs existing in a large size network. As illustrated in Figure 15(a), we notice that each set of flying nodes is organized into cluster supervised by a CH that is the only responsible to communicate with other CHs, ground stations, and the flying nodes belonging to the same cluster.

LCAD (Load Carry and Deliver) [184] is a static routing protocol dedicated exclusively for FANETs. LCAD configures the routing path on the ground before UAVs taking off. UAVs are considered as links between a pair of a source and destination ground stations by collecting data packets,

conveying them, and delivering them to the target destination. If the carrying UAVs are not in the right direction to the destination, other UAVs can take over to deliver the data packets. LCAD is also adopted for delay tolerant networks (DTN) and it is sometimes applied in search and rescue applications. The end-to-end communication in LCAD is divided into three phases (*c.f.*, Figure 15(b)). The first is sending stage where the source ground station transmits the data packet to the first UAV. The second is the conveying stage in which the UAV carries the data packet, and sometimes forwards it to other UAVs. The last phase consists of delivering the data packet to the target ground destination. It should be stressed out that this mechanism does not involve any routing table algorithm.

DCR (Data Centric Routing) [37] is a multicast and static routing protocol. This can be done when a data packet is requested by a number of UAVs and the distribution is carried out using a reactive technique. DCR is adopted in FANETs based on cluster architecture to support several kinds of applications disseminating explicit data for a defined mission area. As shown in Figure 15(c), DCR is based on a Publish-subscribe model, which can connect automatically the data publishers to the data subscribers. The publisher starts the

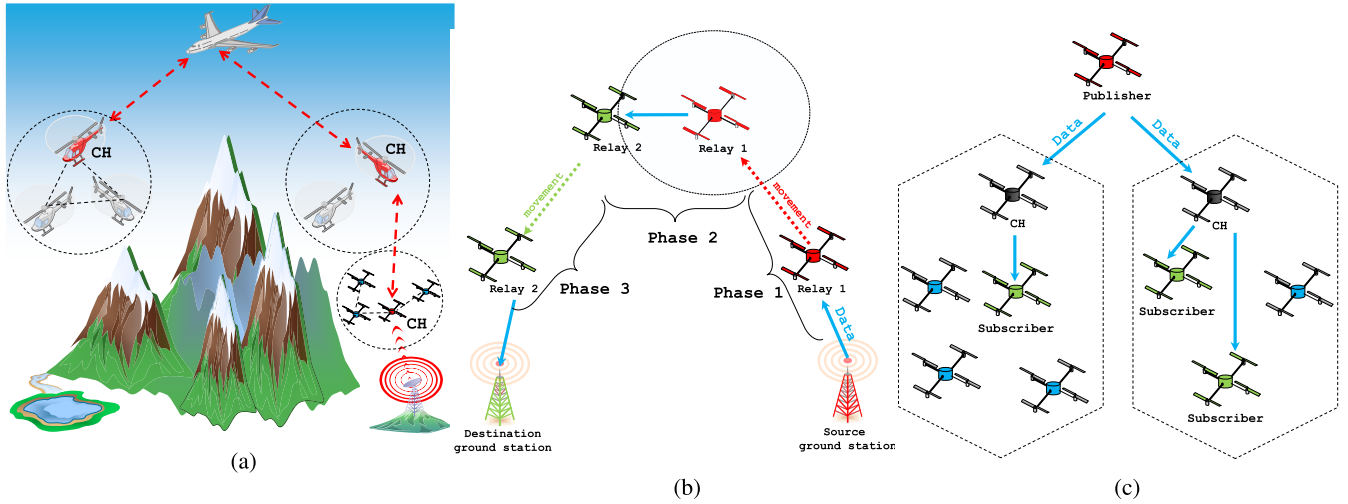


FIGURE 15. Static routing protocols. (a) Multi-Level Hierarchical routing model in FANET. (b) Mechanism of LCAD. (c) Mechanism of DCR.

TABLE 7. Comparative study of topology-based routing protocols.

			Route	Density	Complexity	Advantage	Inconvenient
Proactive	OLSR	Ref. [155]	Dynamic	Low	Medium	Reduces delay and overhead using MPRs.	Increases overhead in high densities.
	D-OLSR	Ref. [163]	Dynamic	Medium	Low	Reduces overhead by reducing MPRs.	Consumes power and bandwidth.
	M-OLSR	Ref. [164]	Dynamic	High	High	Uses motion to enhance MPR selection.	Introduces high overhead.
	CE-OLSR	Ref. [165]	Dynamic	Medium	High	Enhances the next hop selection.	Increases the overheads.
	DSDV	Ref. [166]	Dynamic	Low	Medium	Removes routing loops.	Introduces delay and congestion.
	TBRPF	Ref. [169]	Dynamic	Medium	High	Provides link-quality and less overhead.	Fails in high mobility.
Reactive	BATMAN	Ref. [172]	Dynamic	High	Low	Provides best routes towards all nodes.	Has slow convergence time.
	AODV	Ref. [176]	On demand	High	Medium	Provides high delivery ratio.	Creates high delays.
	TS-AODV	Ref. [177]	On demand	Low	High	Decreases the congestion and bandwidth.	Introduces complex computations.
	M-AODV	Ref. [178]	On demand	High	Medium	Minimizes the delay of delivery.	Does not consider the scalability.
Hybrid	DSR	Ref. [174]	On demand	High	Low	Finds the full path to the destination.	Introduces high overhead.
	HWMP	Ref. [162]	Hybrid	High	High	Adapts to the network variation.	Introduces routing instability.
	ZRP	Ref. [181]	Hybrid	High	High	Enhances the organization of nodes.	Inadequate for high mobility.
	SHARP	Ref. [182]	Hybrid	Medium	High	Limits the overhead by reducing zones.	Increases delay and congestion.
	TORA	Ref. [183]	Hybrid	High	High	Recovers link failures.	Introduces high congestion.
Static	MLHR	Ref. [37]	Static	High	Low	Minimizes the delivery delay.	Does not support high mobility.
	LCAD	Ref. [184]	Static	Low	Low	Maximizes throughput.	Does not support link breakages.
	DCR	Ref. [37]	Static	High	Medium	Multicasts using clusters.	Does not support high mobility.

data broadcasting, which will be intercepted directly or indirectly by the intended UAVs.

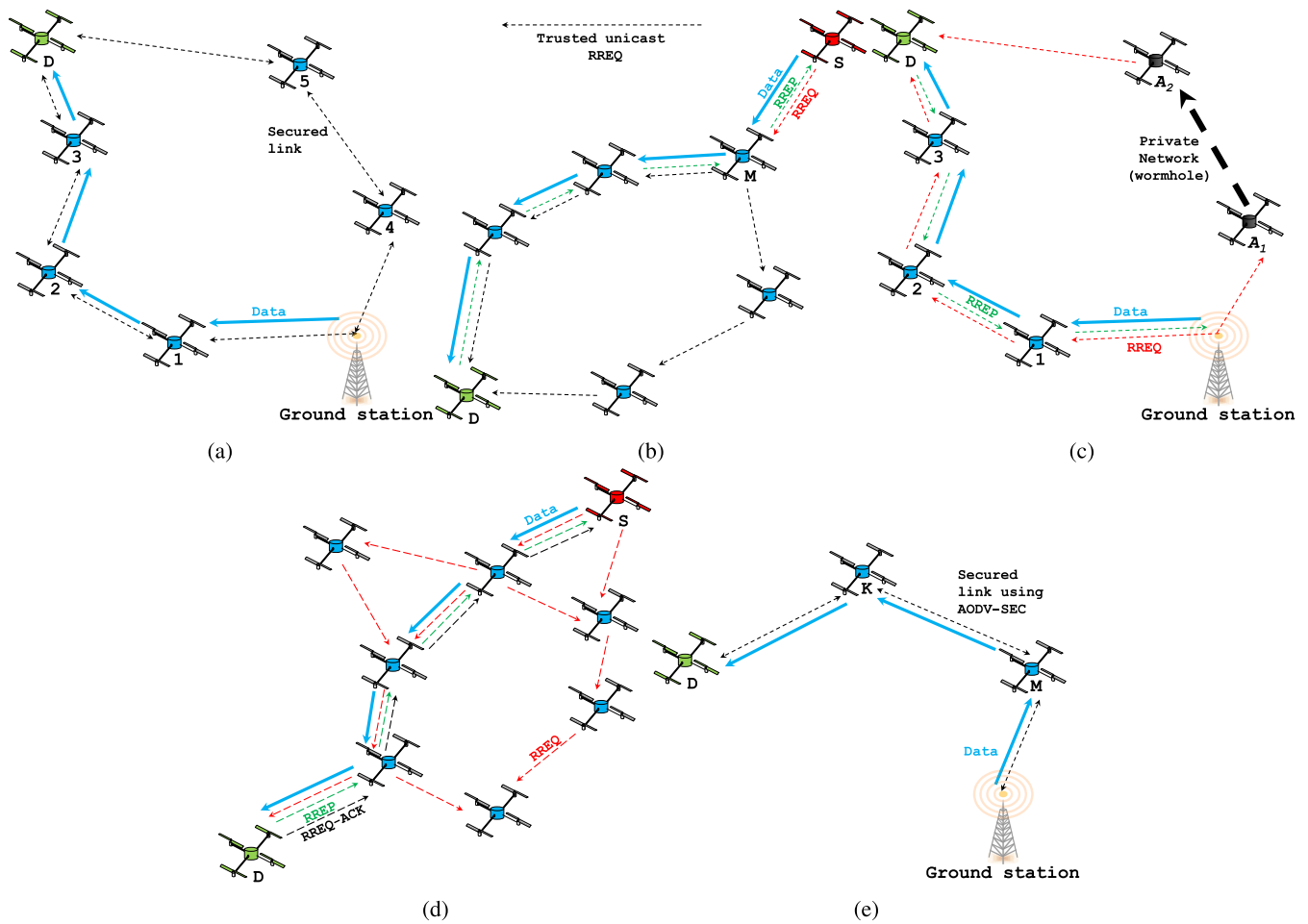
TABLE 7 presents a summary of the topology-based routing protocols described in this subsection. In this category and all others, each protocol is outlined based on crucial parameters, such as the route and how it is established, the required density allowing each protocol to function correctly, and the complexity setup of each protocol and the routing path finding method. Also, the major advantage and inconvenient of each protocol are summarized.

### B. SECURE-BASED ROUTING PROTOCOLS

To ensure confidentiality, privacy, and security of the data transmission, it is important to include a security mechanism into the routing protocols. This category of protocols requires processing that is carried out at each intermediate honest mobile node while respecting the unique features of FANETS.

SUANET (Secure UAV Ad-hoc NETWORK) [185] is a secure-based routing protocol dedicated for FANETS. SUANET uses a key management strategy where multiple keys are deployed between UAVs in order to support confidentiality, authentication, and integrity services. Moreover, the routing process is secured to ensure that all involved UAVs are authenticated and they are able to efficiently establish the shortest routing path towards the target destination. An additional secured strategy is included on another layer than the network one to secure a little more the data delivery between UAVs. Figure 16(a) shows a scenario when the ground station establishes a communication with UAV D. The links between UAVs are maintained and secured using several security parameters to avoid any attacks and to remove any malicious UAVs.

PASER (Position-Aware, Secure, and Efficient mesh Routing) [186] is a secure routing protocol that can be adopted for FANETS. PASER is based on cryptographic functions



**FIGURE 16.** Secure-based routing protocols. (a) Mechanism of SUANET. (b) Mechanism of PASER. (c) Mechanism of SUAP. (d) Mechanism of AODV-SEC. (e) Mechanism of SRPU.

to protect the exchanged routing packets in the network. Moreover, the routing paths have to be composed of valid UAVs and must be empty of malicious UAVs. PASER can quickly detect malicious UAVs trying to compromise the routing process or to join illegally the network and exclude them (e.g., trying to modify the expected behavior of a UAV). This can be done by using a centralized approach that operates at the ground station and by refreshing periodically and dynamically the keys, respectively. Figure 16(b) depicts a scenario where UAV *S* wants to establish a communication with UAV *D* by initializing a discovery process. Two different sides can be distinguished: (i) the routing side and (ii) the security side. On the first side, the intermediate UAVs forward unicastly the RREQ packet, since they are both registered and know the integral path to UAV *D* that makes a routing decision by responding using an RREP packet. As for the second side, the non-trusted links (e.g., the links between UAV *S* and UAV *M*) use the asymmetric scheme provided by PASER in order to establish a trusted relationship, and thus to secure the exchange of messages (i.e., the messages are secured using cryptographic operations and

asymmetric-key-based functions). However, for the trusted links, PASER uses the symmetric scheme.

SUAP (Secure UAV Ad hoc routing Protocol) [187] is a secure-based routing protocol for FANETs based on AODV [176]. The aim of SUAP is to ensure the message authentication and to provide both detection and prevention against wormhole attacks. The exchanged control packets include static (e.g., IP addresses) and dynamic fields (e.g., hop count), which are protected using digital signatures and hash chains, respectively. These packets are decrypted by the UAVs receiving them based on the public key of the sender. Moreover, geographical leashes are adopted to compute the correlation between the hop count and the distance transited by the packets. This can be done by maintaining the links with the neighboring UAVs. Malicious modifications can be also avoided by signing all the fields of the messages. To better explain SUAP, we consider the example in Figure 16(c). UAV *A*<sub>1</sub> and UAV *A*<sub>2</sub> are two attackers while the ground station is supposed to be the victim. A discovery process is initiated by the ground station to communicate with UAV *D* by broadcasting an RREQ packet across the network.



TABLE 8. Comparative study of secure-based routing protocols.

		Route	Density	Complexity	Advantage	Inconvenient
Secure	SUANET Ref. [185]	Dynamic	Medium	High	Enhances security and quality of links.	Lacks the stability of links.
	PASER Ref. [186]	On demand	High	Medium	Ensures the scalability and security.	Introduces high overhead and delay.
	SUAP Ref. [187]	On demand	High	Medium	Protects the flooding against attacks.	Does not deal with the high mobility.
	AODV-SEC Ref. [188]	On demand	High	Medium	Secures the discovery process.	Uses complex processing.
	SRPU Ref. [189]	On demand	High	Medium	Enhances security mechanisms	Introduces more overhead.

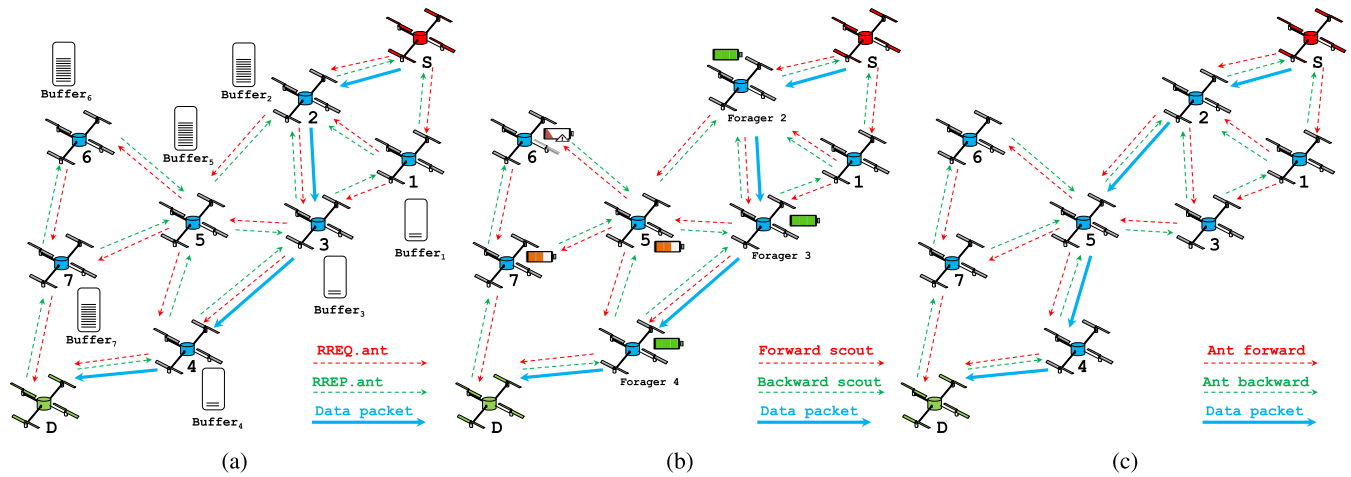


FIGURE 17. Bio-inspired routing protocols. (a) Mechanism of APAR. (b) Mechanism of BeeAdhoc. (c) Mechanism of POSANT.

Then, each UAV unicastly forwards the RREQ to its neighbor UAVs.  $A_1$  and  $A_2$  make a colluding attack by recording the intercepted RREQ packet at a certain location based on a high-speed private network existing between them that can be considered as a wormhole. To address this problem, SUAP makes a set of verifications to detect automatically any wormhole links by computing the hop count based on the transited distance.

AODV-SEC (Ad hoc On-demand Distance Vector-Secure) [188] is a secured version of the known AODV protocol [176] and it can be applied to FANETs. Public key infrastructure and certificates are used as a trust anchor. The aim of AODV-SEC is to secure the discovery process along with its exchanged control packets. Moreover, AODV-SEC authenticates the communicating nodes, the intermediate nodes separating them, and at the same time, excluding the non-trusted nodes. In the example shown in Figure 16(d), the route discovery in AODV-SEC is similar to that of the classical AODV. However, the difference lies in using a new type of control packets called RREQ-ACK that is sent before the RREP packet. RREQ-ACK packets are both used to avoid fake RREP packets and to validate their incoming.

SRPU (Secure Routing Protocol for UAVs) [189] is a secure-based routing protocol based on the well-known AODV [176] and it is dedicated for FANETs. The MDD (Model Driven Development) scheme is used to make the exchange of packets more secure. It is a reactive protocol (*i.e.*, a discovery process is carried out only when a communication is needed) where several mechanisms are adopted

inspired by the protocol AODV-SEC [188]. In the scenario depicted in Figure 16(e), three UAVs are deployed in the sky and the ground station is sending a data traffic to UAV  $D$  via UAVs  $M$  and  $K$ . When attacks between UAVs  $M$  and  $D$  are trying to alter the exchanged control packets, SRPU calculates the distance transited by packets and their expiration times. This can allow other UAVs to determine whether or not the packet has been altered.

TABLE 8 summarizes the secure-based routing protocols discussed above.

### C. BIO-INSPIRED ROUTING PROTOCOLS

Inspiration from biological behaviors of insects, such as bee, ant, or even particle swarm, constitutes an important support for different FANET issues, and especially for establishing communications between UAVs [190]. Many bio-inspired routing protocols have been proposed in the literature trying to solve different kinds of routing issues.

APAR (An ant colony optimization based Polymorphism-Aware Routing algorithm) [191] is a swarm-based routing protocol dedicated for FANETs. APAR combines the ant colony optimization algorithm with the well-known DSR [174]. During the discovery process, the levels of pheromones, as well as the transited distance by packets, are used as a selection criterion for the routing paths. The congestion (*i.e.*, the buffer occupancy and the channel load) and the stability (*i.e.*, the mobility and the connectivity) of the routing paths are also taken into account during the routing decision. Figure 17(a) depicts the scenario where a UAV  $S$

**TABLE 9.** Comparative study of bio-inspired routing protocols.

			Route	Density	Complexity	Advantage	Inconvenient
Bio	APAR	Ref. [191]	On demand	High	Medium	Avoids congestion and link failures.	Introduces overheads and delays.
	BeeAdhoc	Ref. [192]	On demand	High	High	Enhances memory storage and bandwidth.	Complex behaviors modeling.
	POSANT	Ref. [193]	Dynamic	Medium	High	Supports network fragmentation.	Uses quasi-static topology.

wants to engage a communication with UAV  $D$ . A routing process based on the exchange of RREQ. ant and RREP. ant between UAVs to find the most connected (*i.e.*, UAVs close to each other) and the less congested routing path (*i.e.*, UAVs having less saturated buffers).

BeeAdhoc (Bee colony algorithm for FANET routing) [192] is inspired by the bee-hive functioning principle based on a clear distribution of responsibilities among the bees (UAVs). Two different groups of bees: (i) forager bees and (ii) scouts. Two different stages are considered during the functioning of BeeAdhoc: (i) Scouting stage and (ii) Resource foraging stage. In the first stage, forward and backward scouts including the source ID, the number of hops, and the minimal residual energy, are flooded across the network to establish multiple paths between the communicating nodes. In the second stage, the data packets are delivered from the source to the destination using the forager bees. As an example, we consider the scenario of Figure 17(b). Whenever UAV  $S$  has a need to establish a communication with UAV  $D$ , a forward scout is broadcasted over the network while considering the residual energy of each transited UAV and the hop count. A backward scout is sent back to UAV  $S$  through the multiple discovered routes. The selected routing path (*i.e.*, the shortest path composed of UAVs having a high energy level) is composed of forager-bees that are in charge of transmitting the data packets.

POSANT (Position Based Ant Colony Routing Algorithm) [193] is an ant colony-based routing protocol firstly dedicated for MANETs and it can be applied to FANETs. POSANT uses geographical positions in the heuristic during the discovery process allowing each UAV to select the appropriate next hop. This can minimize the number of ant generations (*i.e.*, control messages) while reducing the end-to-end delivery delay. A communication between UAV  $S$  and UAV  $D$  is done only after a routing path is established between them (*c.f.*, Figure 17(c)). Before that, only the exchange of forward and backward ants is used to plot the shortest path between the communicating UAVs. To keep the number of the ant generations as small as possible, the geographical locations of UAVs are used as a heuristic value.

The discussed bio-inspired routing protocols are summarized in TABLE 9.

#### D. HIERARCHICAL-BASED ROUTING PROTOCOLS

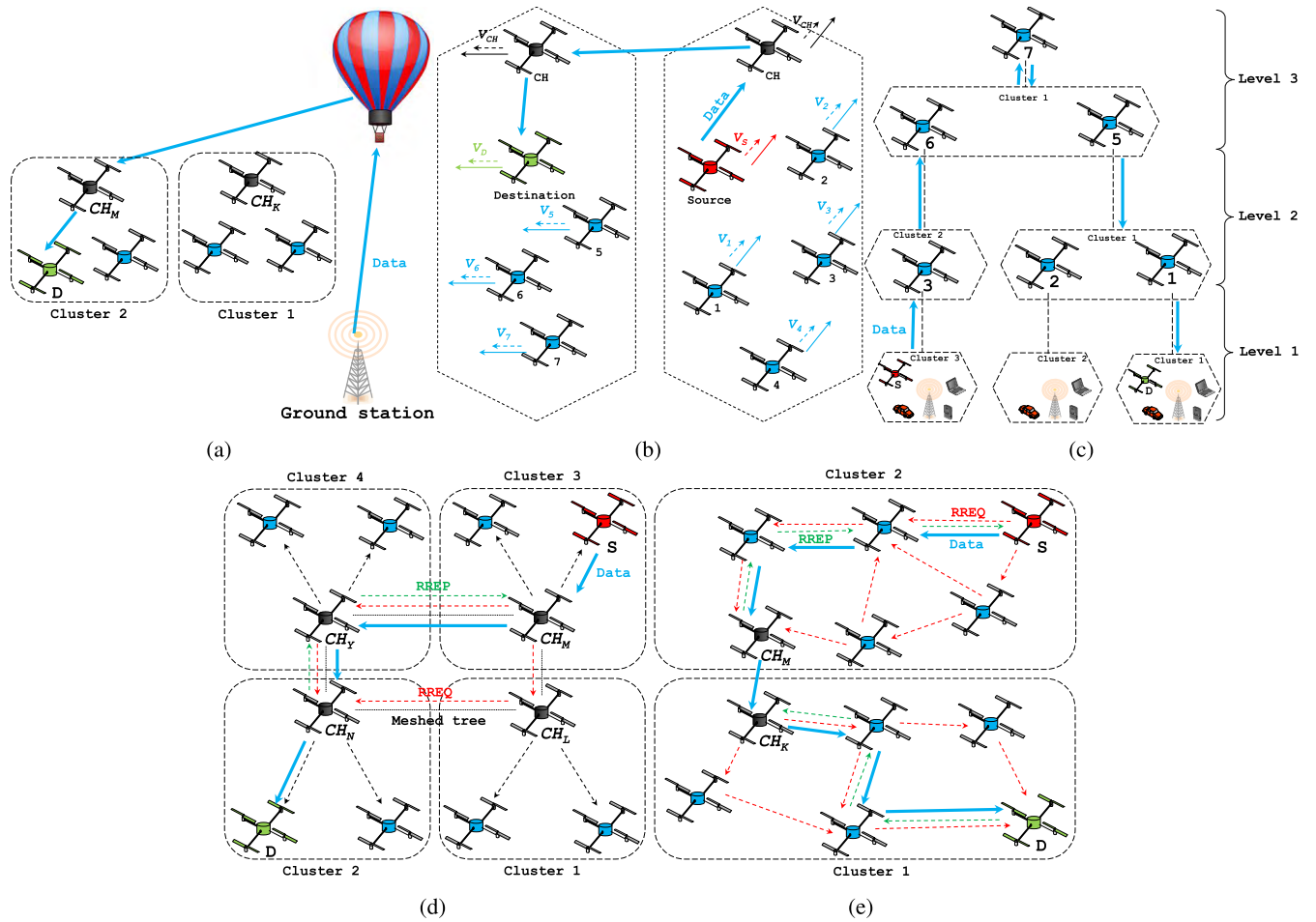
The hierarchical strategy is generally based on the formation of clusters where each one is supervised by a CH. This is advantageous to both decrease the number of packets transmitted to ground stations and minimize the energy

consumption among UAVs. As a drawback, hierarchical protocols suffer from high complexity in forming clusters, and in the majority of cases, they do not support frequent link disconnections.

CA (Clustering Algorithm) [194] is a hierarchical routing protocol based on dynamic cluster formation according to the adopted mission in FANET. CA constructs clusters on the ground, which are updated according to the mission. Each cluster is represented by a CH that is selected by the ground station using its geographical position. It should be stressed that CA requires a balloon (*i.e.*, an aerostat flying above the UAVs) where the ground station communicates directly with it. The balloon, in turn, exchanges information with UAVs. When the ground station wants to communicate with UAV  $D$ , it communicates directly with the balloon (*c.f.*, Figure 18(a)). The balloon forwards the packet to the appropriate cluster through its CH (*i.e.*,  $CH_M$ ), where the packet will be delivered to UAV  $D$ .

MPCA (Mobility Prediction Clustering Algorithm for UAV Networking) [195] is a hierarchical routing protocol trying to design clusters based on the movement prediction of UAVs. The mobility prediction is estimated based on two parameters: (i) link expiration time and (ii) Dictionary Trie Structure. The first parameter is calculated between each pair of UAVs using their positions and speed. The second parameter is the probability of a UAV staying in the cluster. Consequently, these two parameters are the keys to form more stable clusters and to enhance the performance of the network. The formation of clusters can be easily done based on the speeds, the velocities, and the positions of UAVs (*c.f.*, Figure 18(b)). The communication is performed based on the inter-cluster and intra-cluster mechanisms according to the kind of UAVs (*i.e.*, when communicating UAVs are belonging to the cluster or not).

EHSR (Extended Hierarchical State Routing Protocol) [196] is a hierarchical routing protocol based on a cluster architecture. The clustering is carried out based on levels that are defined using both a logical and physical basis. On each level, UAVs form clusters in which an elected cluster-head represents each one of them. The different cluster-heads at the lower level, in turn, form another cluster on the next higher level. EHSR consists of three levels: (i) UAV network, (ii) backbone network, and (iii) ground network, where each node possesses a unique hierarchical ID (HID). A proactive mechanism is adopted by the cluster-heads by collecting link state information about the cluster members and share it with their fellow cluster-heads on the higher levels. The same process is done at the higher levels, thus defining all the possible



**FIGURE 18. Hierarchical-based routing protocols. (a) Mechanism of CA. (b) Mechanism of MPCA. (c) Mechanism of EHSR. (d) Mechanism of MMT. (e) Mechanism of DTM.**

routing paths within the hierarchy. The clustering architecture of EHSR is shown in Figure 18(c). In level 1, four different clusters are created, which are supervised by a cluster-head each (*i.e.*, UAV 1, 2, 3, and 4). The cluster-heads act as cluster members in level 2, which are supervised by two other cluster-heads (*i.e.*, UAV 5 and 6). These two cluster-heads are also cluster members of a cluster that is supervised by another cluster-head (*i.e.*, UAV 7) in level 3. When UAV *S* located at the level 1 wants to communicate with UAV *D* located at the same level, but in a different cluster, the data packet transits through the upper levels according to the architecture until it gets UAV *D*.

MMT (Multi Meshed Tree Protocol) [197] is a cluster-based routing protocol destined for FANET. MMT creates several clusters that are determinable based on their size and their maximum hop count from their respective CHs. Each cluster is composed of a group of UAVs or cluster clients (CCs) that are connected to their CH based on the mesh tree principle. MMT simultaneously establishes proactive routes within each cluster to allow CCs to communicate directly with their CH. A reactive approach is adopted for inter-cluster communications, which is always based on the meshed

tree principle, thus reducing to flood the entire of the network. In the case when a UAV leaves a cluster losing the connectivity to its CH, the UAV is still able to communicate with its previous CH through another routing path. As shown in Figure 18(d), MMT organizes the network based on the mesh tree principle. For instance, when UAV *S* wants to engage a communication with UAV *D* that is belonging to another cluster. The data packet is directly sent to  $CH_M$  (*i.e.*, the cluster-head of UAV *S*) where a discovery process is initiated to reach the cluster of UAV *D*. Once a path is established, the data packet is sent to the destined cluster, which will be then sent to UAV *D*.

DTM (Disruption Tolerant Mechanism) [198] adopts a cluster architecture supported by a reactive routing mechanism based on the well-known AODV [176] and it is dedicated to FANETs. During the discovery process, AODV is only applied within each cluster to reduce the network overhead. If the destination UAV belongs to the cluster, the packet is delivered to it automatically. Otherwise, the packet is delivered hop by hop. Moreover, the positions, the velocities, and the speeds are all considered by DTM. In the case of a link failure, the packets are buffered for a maximum

**TABLE 10.** Comparative study of hierarchical-based routing protocols.

		Route	Density	Complexity	Advantage	Inconvenient	
Hierarchical	CA	Ref. [194]	Dynamic	Medium	High	Ground assistance of the routing.	Requires an aerostat.
	MPCA	Ref. [195]	Dynamic	Medium	High	Predicts link failures.	Fails when unpredictable motion.
	EHSR	Ref. [196]	Dynamic	Medium	Medium	Increases the scalability.	Needs a ground backbone.
	MMT	Ref. [197]	Dynamic	High	High	It manages frequent link failures at once.	High overheads to form clusters.
	DTM	Ref. [198]	On demand	High	High	Increases delivery ratio and throughput.	Employs delay tolerant principle.

time-to-live and DTM keeps track of the topology changes and delivers the message as quickly as possible when a new path towards the destination is found. To efficiently maintain the clusters, each cluster-head exchanges Hello packets including the identifier of both the cluster-head and the cluster. This is sufficient to acknowledge the internal connectivity. Figure 18(e) shows the functioning principle of DTM to send a data packet from UAV  $S$  to UAV  $D$ . The reactive mechanism of AODV is adopted in the two clusters to find the adequate routing path while considering its connectivity degree. The inter-cluster communication is carried out hop-by-hop between the cluster-heads  $CH_M$  and  $CH_K$ .

TABLE 10 outlines the reviewed protocols in this subsection.

### E. ENERGY-BASED ROUTING PROTOCOLS

Unbalanced energy consumption among UAVs is considered as a non-trivial problem, particularly, given the unfair selection of UAVs constituting the routing path without taking into account their energy levels. An adequate solution to this problem should be aware of the remaining energy available in each UAV which can be a candidate to constitute a given path. In addition, a UAV with low residual energy has to be spared from any participation in a packet routing or wireless communications excluding some exceptional cases.

CBLADSR (Cluster-Based Location-Aided Dynamic Source Routing) [199] is an energy-efficient routing protocol harmonizing three different concepts: (i) a cluster architecture, (ii) a reactive routing strategy based on the well-known DSR [174], and (iii) a geographical routing. The first concept is created based on stable sets of UAV swarms. As for the second and the third concepts, they are combined based on the embedded GPS in each UAV to perform a discovery process as well as the routing maintenance. The cluster-heads are elected using the node-weight heuristic algorithm by considering three parameters, such as the speed of UAVs, their connectivity degree with each cluster-head, and the energy level of the cluster-heads. Moreover, CBLADSR uses a short transmission range to communicate with cluster members and a long transmission range with distant destinations. UAV  $S$  in Figure 19(a) tries to establish a communication path with UAV  $D$  over a network organized into clusters. Since UAV  $S$  and  $D$  do not belong to the same cluster, a route discovery has to be initiated by taking into account the connectivity and the residual energy of each transited UAVs. Consequently, the most connected routing path composed of UAVs having high energy levels.

EALC (Energy Aware Link-based Clustering) [200] is an energy-based routing protocol dedicated for FANETs. The main aim of EALC is to reduce the overhead by keeping simpler the clustering formation along with a higher lifetime. Moreover, the communication range of UAVs is dynamic according to the network necessity. The clustering algorithm is based on the K-means density variant using the degree of the neighborhood in order to select the appropriate cluster-head. The distance and the energy level of the neighbors are also considered for the cluster-head selection. This can improve the lifetime of each cluster and enhance the energy consumption by efficiently adjusting the communication power of UAVs according to the distance. Figure 19(b) shows a scenario where two clusters are formed based on the different requirements mentioned above. When UAV  $S$  starts the data transmission towards the ground station, it first sends its data packet to its cluster-head  $CH_M$ . Then, it is the responsibility of  $CH_M$  to forward the data packet across the network (*i.e.*, the data packet is transited through the other cluster-heads) until it will be delivered to the ground station.

EPLA (Energy-Efficient Packet Load Algorithm) [201] is an energy-efficient relaying scheme dedicated for FANETs. EPLA aims to extend the network lifetime while ensuring an acceptable data rate. An optimal transmission schedule based on standard optimization techniques is designed to reduce the energy consumption under guaranteed bit error rates. The number of UAVs is increased significantly by designing a computationally efficient sub-optimal algorithm in order to minimize the scheduling complexity, where rate adaptation and energy balancing are combined and done in a recursive alternating way. EPLA also studies the different aspects of UAVs, such as the effect of UAV trajectories on the network lifetime and routing packets. Figure 19(c) shows a scenario where a data packet is transited from UAV  $S$  to the ground station through UAVs having high energy levels, thus carrying out a balanced energy consumption. The trajectories of relaying UAVs are also taken into account in the data delivery, where the UAVs proving a stable path are selected to route the data packet.

IMRL (Localization and Energy-Efficient Data Routing for Unmanned Aerial Vehicles) [202] is a novel routing mechanism for FANETs, which is based on the geographical positions of UAVs and their residual energy levels. In the first step, IMRL calculates the positions of unknown UAVs based on the fuzzy logic inference using the received signal strength indication (RSSI) between UAVs. Secondly, to minimize the energy consumption and to enhance the network

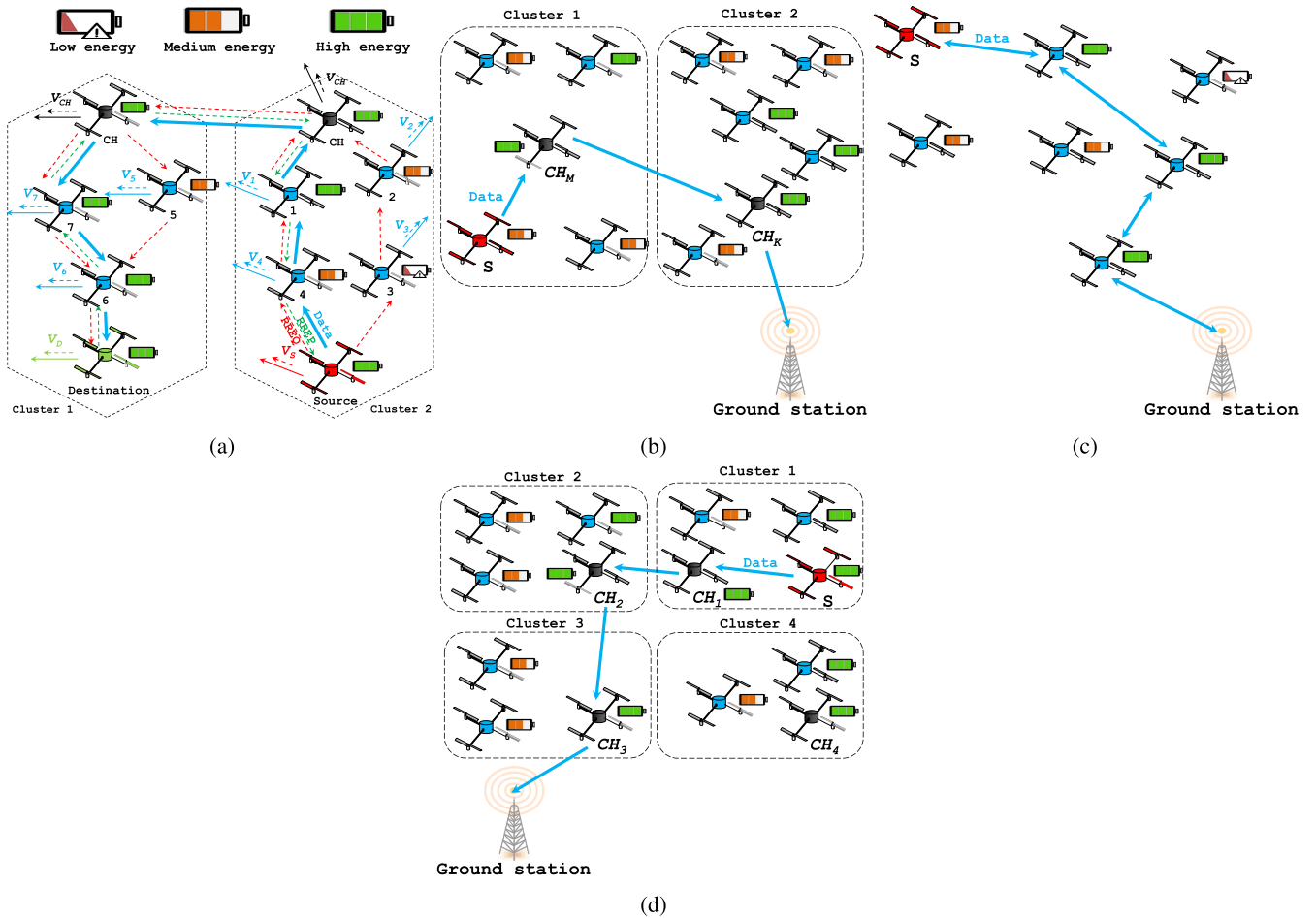


FIGURE 19. Energy-based routing protocols. (a) Mechanism of CBLADSR. (b) Mechanism of EALC. (c) Mechanism of EPLA. (d) Mechanism of IMRL.

TABLE 11. Comparative study of energy-based routing protocols.

	Route	Density	Complexity	Advantage	Inconvenient	
Energy	CBLADSR Ref. [199]	On demand	High	Medium	Provides high delivery ratio.	Generates high delay and overhead.
	EALC Ref. [200]	Dynamic	High	High	Provides low packet losses and robust link.	High energy consumption for CHs.
	EPLA Ref. [201]	Dynamic	Low	High	Ensures energy balancing among UAVs.	Does not consider link failures.
	IMRL Ref. [202]	Dynamic	Low	High	Improves the network lifetime.	Does not study the high mobility.

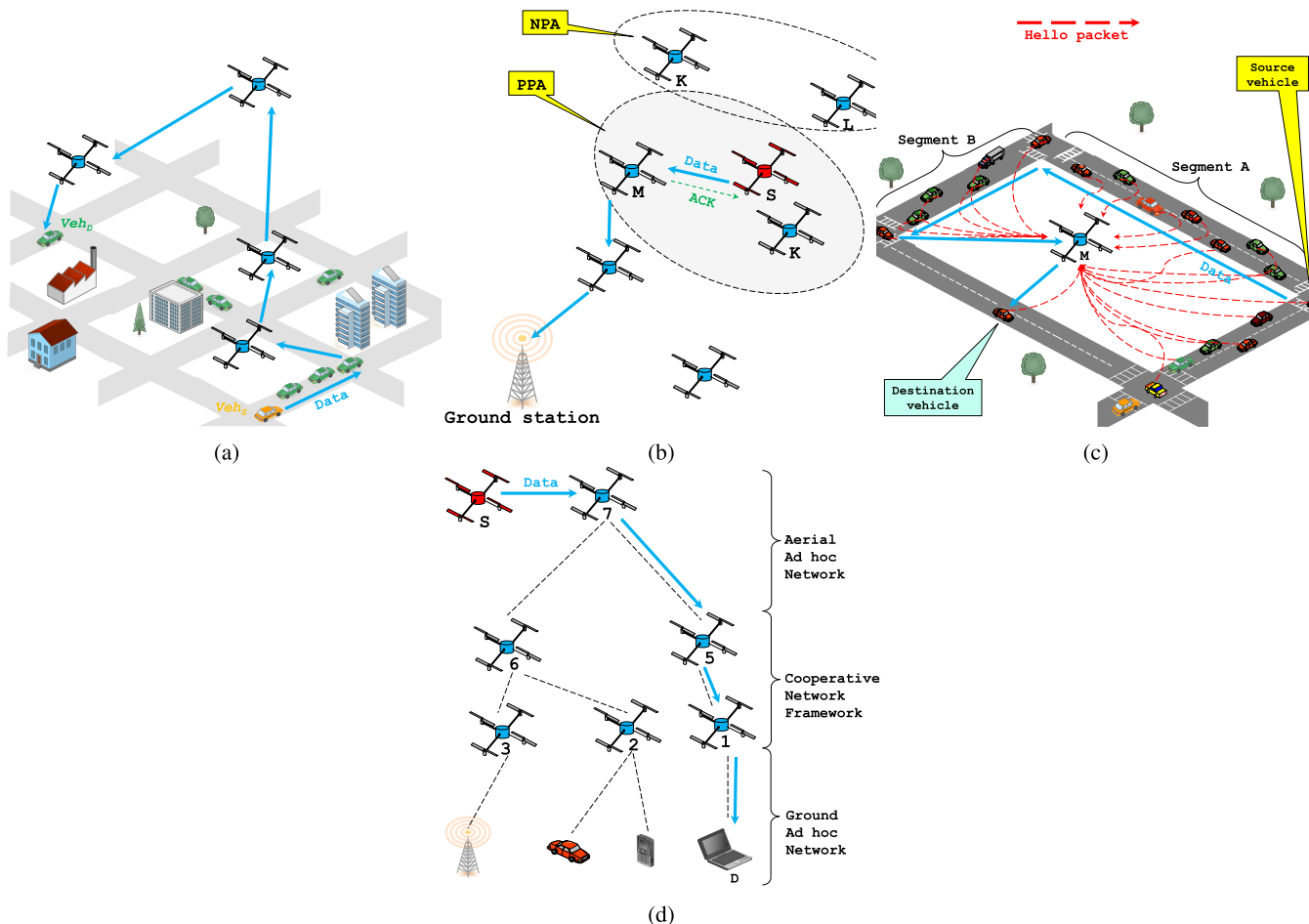
lifetime, the network is organized into clusters and a new strategy is adopted to select the next hop cluster-heads using the localization algorithm introduced in the first step. The election of the CHs also considers the parameters, such as the residual energy of each CH, the density of the next elected CH, the distance separating the current and the next CH, and the distance between the next CH and the ground base station. Figure 19(d) depicts a scenario where a set of clusters is formed in the sky (i.e., four clusters) based on the mechanism of IMRL. When a communication should be established between UAV *S* and the ground station, a data packet is transited through the elected CHs (i.e.,  $CH_1$ ,  $CH_2$ , and  $CH_3$ ) constituting the shortest path to the ground station.

TABLE 11 presents a summarize of the discussed energy-based routing protocols.

### F. HETEROGENEOUS-BASED ROUTING PROTOCOLS

Generally, FANETs interact with different kinds of networks, and especially those located on the ground, such as MANETs, VANETs, or even fixed nodes. This concept is adopted in various applications that need a robust data exchange between the mobile nodes. Only a few heterogeneous routing protocols are proposed in the literature.

CRUV (Connectivity-based Traffic Density Aware Routing using UAVs for VANETs) [203] is a heterogeneous routing protocol for VANETs using UAVs as a support during the routing process. CRUV is an enhanced version of [204], [205], which exploits the exchange of Hello packets between vehicles to calculate the routing segments towards the target having a high degree of connectivity. The existing UAVs in the sky try to collect the connectivity information



**FIGURE 20.** Heterogeneous-based routing protocols. (a) Mechanism of CRUV. (b) Mechanism of XLinGo. (c) Mechanism of UVAR. (d) Mechanism of DPTR.

of the segments and share it with all vehicles located at each intersection in range. This is because the intersections are the only places where routing decisions are carried out. In CRUV, UAVs can also be selected as next hops in the case when there are no connected segments on the ground towards the destination. Figure 20(a) exemplifies a scenario when a source vehicle  $Veh_S$  wants to send a data packet to a destination vehicle  $Veh_D$ . It selects the shortest and most connected segments to transit the data packet to the target destination. In the case when the network is poorly dense, the closest UAV is selected to continue delivering the packet in the sky until  $Veh_D$  will be in range or until a connected segment on the ground is found.

XLinGo (Cross-layer Link quality and Geographical-aware beacon-less opportunistic routing protocol) [206] enhances a real-time transmission of multiple video flows simultaneously sent over FANETs by maintaining reliable multi-hop routing paths. In order to deal with the high mobility of UAVs and the frequent disconnections, XLinGo estimates a set of human-related and cross-layer parameters to improve the QoS of the established routing paths and to appropriately select the most stable path. To select the

next hops, XLinGo adopts the concept of Dynamic Forwarding Delay (DFD). All neighboring UAVs receiving the data packet calculate their DFD values based on their positions. The UAV having the lowest DFD forwards the packet first. The example of Figure 20(b) shows the transmission of a video flow from UAV  $S$  to a ground station where its position is supposed to be known. After including its location, UAV  $S$  broadcasts a data packet to all its neighbors UAVs  $M$ ,  $K$ ,  $N$ , and  $L$ . Only one of the neighboring UAVs is allowed to forward the data packet by calculating the DFD metric and the required energy to transmit. Based on this information, two different areas are differentiated: (i) PPA (Positive Progress Area) and (ii) NPA (Negative Progress Area). All UAVs belonging to NPA (*i.e.*, UAV  $N$  and  $L$ ) have to drop the intercepted data packet, since the UAVs belonging to PPA (*i.e.*, UAV  $M$  and  $K$ ) are considered as the most appropriate to relay the data packet. UAV  $M$  obtains the lowest DFD and it is selected to forward the data packet to UAV  $D$  based on the same process. An acknowledgment (ACK) is forwarded back to UAV  $S$  by UAV  $M$  in order to continue sending the remaining subsequent packets.

TABLE 12. Comparative study of heterogeneous-based routing protocols.

			Route	Density	Complexity	Advantage	Inconvenient
Hetero	CRUV	Ref. [203]	Dynamic	Medium	High	UAV assistance of the routing	Does not fully exploit UAVs.
	XLinGo	Ref. [206]	Dynamic	Medium	High	Avoids congestion and reduces overhead.	One UAV produces video.
	UVAR	Ref. [207]	On demand	Medium	High	Fully exploits UAVs.	Causes high delays and energy fail.
	DPTR	Ref. [208]	Dynamic	Medium	High	Enhances delay and throughput.	Does not consider ground mobility.

UVAR (UAV-Assisted VANET Routing Protocol) [207], [209] is an enhanced routing version of CRUV [203]. UVAR fully exploits the existing UAVs in the sky both during the data delivery and the estimation of the connectivity degree of each segment in range. A score is assigned by the hovering UAV to each segment based on four metrics: (i) the traffic density, (ii) the connectivity between the two intersections, (iii) the real distribution of vehicles, and (iv) the distance separating the communicating vehicles. All these metrics are calculated by intercepting the periodical exchange of Hello packets between vehicles on the ground. This allows to avoid the different obstacles on the ground and to support the routing process when the network is intermittently connected. Consider the example shown in Figure 20(c) where a UAV covers a zone of four road segments. By intercepting the exchanged Hello packets between vehicles, UAV  $M$  can automatically calculate a score for each road segment, send this information to all vehicles located at each intersection, and forward the packet when the road segments are sparsely connected. The data packet is transmitted through the segments  $A$ ,  $B$ , and then the packet will be delivered to the target destination through UAV  $M$ .

DPTR (Distributed Priority Tree-Based Routing Protocol) [208] is a routing protocol operating between aerial and ground ad hoc networks, where a solution for topological formations are performed. DPTR provides a solution solving the network sparseness (*i.e.*, either the aerial or the ground fragmentation) by using the properties of a Red-Black (R-B) tree. Additional rules are added to provide the required support, which allows DPTR to be deployed over several distributed ad hoc networks. These rules are extended to build the network and the routing paths and to avoid network isolations. The different control packets are delivered over different channels and rates, where DPTR provides a considerable effort of management and control. As shown in Figure 20(d), DPTR starts identifying ground and aerial nodes and interfacing using neural structure. Secondly, DPTR forms the R-B tree in order to make more efficient the communication, *e.g.*, between UAV  $S$  located in the sky and node  $D$  located on the ground. Finally, three cooperative structures are designed: (i) Aerial Ad hoc Network, (ii) Cooperative Network Framework, and (iii) Ground Ad hoc Network.

A summarize of the heterogeneous-based routing protocols is presented in TABLE 12.

### G. POSITION-BASED ROUTING PROTOCOLS

In this category, each UAV assumes the knowledge of its own position using the embedded GPS. In most of the cases,

the sender knows the position of the receiver using a location service and it communicates without performing a discovery process. Since several techniques are used to avoid disconnections or to recover when they occur, the position-based routing protocols are the most adequate for FANETS.

#### 1) REACTIVE

Sometimes the senders need to establish on-demand full routing paths to their target receivers based on a discovery process. In the case of disconnection, this kind of strategy needs to recover quickly in order to find other alternative paths to continue the data transmission.

ARPAM (Ad hoc Routing Protocol for Aeronautical MANETs) [210] is an on-demand routing mechanism dedicated for FANETS using the same strategy applied in AODV [176]. ARPAM exploits geographical locations of UAVs to plot the shortest path between a pair of communicating UAVs. Also, the speeds and velocities are exploited to provide stable paths and they can be used as metrics during the routing decision. Moreover, ARPAM uses a maintenance technique aiming to recover a path failure when it occurs, and especially for certain applications that are supported by ARPAM, such as video on demand (VoD) or voice over IP (VoIP), which needs a permanent connectivity. Same as AODV, ARPAM initiates a discovery process by flooding an RREQ packet to establish the most stable and shortest routing paths between UAV  $S$  and UAV  $D$  (*c.f.*, Figure 21(a)). The RREQ packet includes the speed and the velocity of UAV  $S$  in order to be used by the intermediate UAVs to calculate its current and future positions that change due to its high mobility. This information can be also used as a metric during the routing decision by providing the distance that the packet has transited.

RGR (Reactive-Greedy-Reactive) [211] is a routing protocol dedicated for FANETS combining two modes: (i) reactive mode and (ii) geographical mode. When the network suffers from a reduced number of disconnections, the first mode is based on the well-known AODV [176]. However, when the topology of the network frequently changes due to both the high mobility and the reduced number of UAVs, the GGF (Greedy Geographic Forwarding) mode is used to continue forwarding the data packets. As a hypothesis, each UAV has a knowledge of the positions of the neighboring UAVs based on the neighbor discovery process. The position of the destination is supposed to be known to forward the data packets to the closest UAV to the destination when AODV fails. When UAV  $S$  wants to engage a communication with

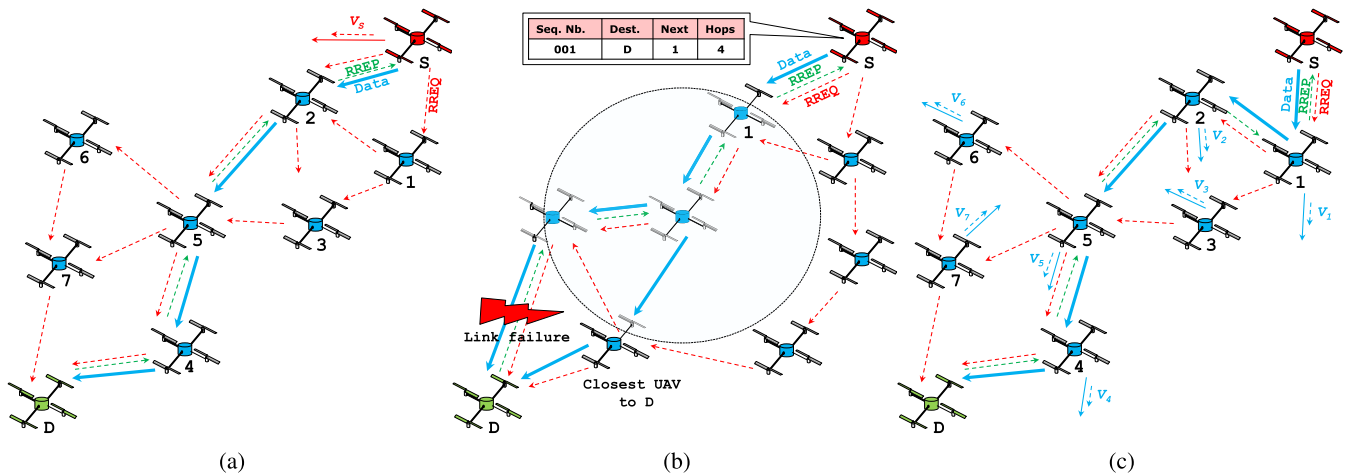


FIGURE 21. Reactive-based routing protocols. (a) Mechanism of ARPAM. (b) Mechanism of RGR. (c) Mechanism of MUDOR.

UAV  $D$ , it initiates a discovery process (same as AODV) by using RREQ and RREP packets including the geographical position of the source and the destination, respectively (*c.f.*, Figure 21(b)). The GGF mode is activated only when there is a disconnection in the already established path to the destination.

MUDOR (Multipath Doppler Routing) [212], [213] is a position-based reactive routing protocol inspired by DSR [174] and designed exclusively for FANETs. The stability and the expiration time are the key criteria to establish any routing paths based on the Doppler shift of the control packets. MUDOR initiates a nondisjoint discovery process by flooding an RREQ packet over the network, which contains the Doppler value of each transited UAV. The routing decision considers the paths having the longest lifetime while taking into account all the computed Doppler values. An RREP is generated and sent unicastly through the selected path to the source UAV. Based on the Doppler values collected during the discovery process (*i.e.*, the broadcast of RREQ), the relative velocity between any two neighboring UAVs is defined. MUDOR allows to select the most stable succession of UAVs (*i.e.*, same velocities and speeds) by sending unicastly an RREP packet towards UAV  $S$  (*c.f.*, Figure 21(c)).

## 2) GREEDY

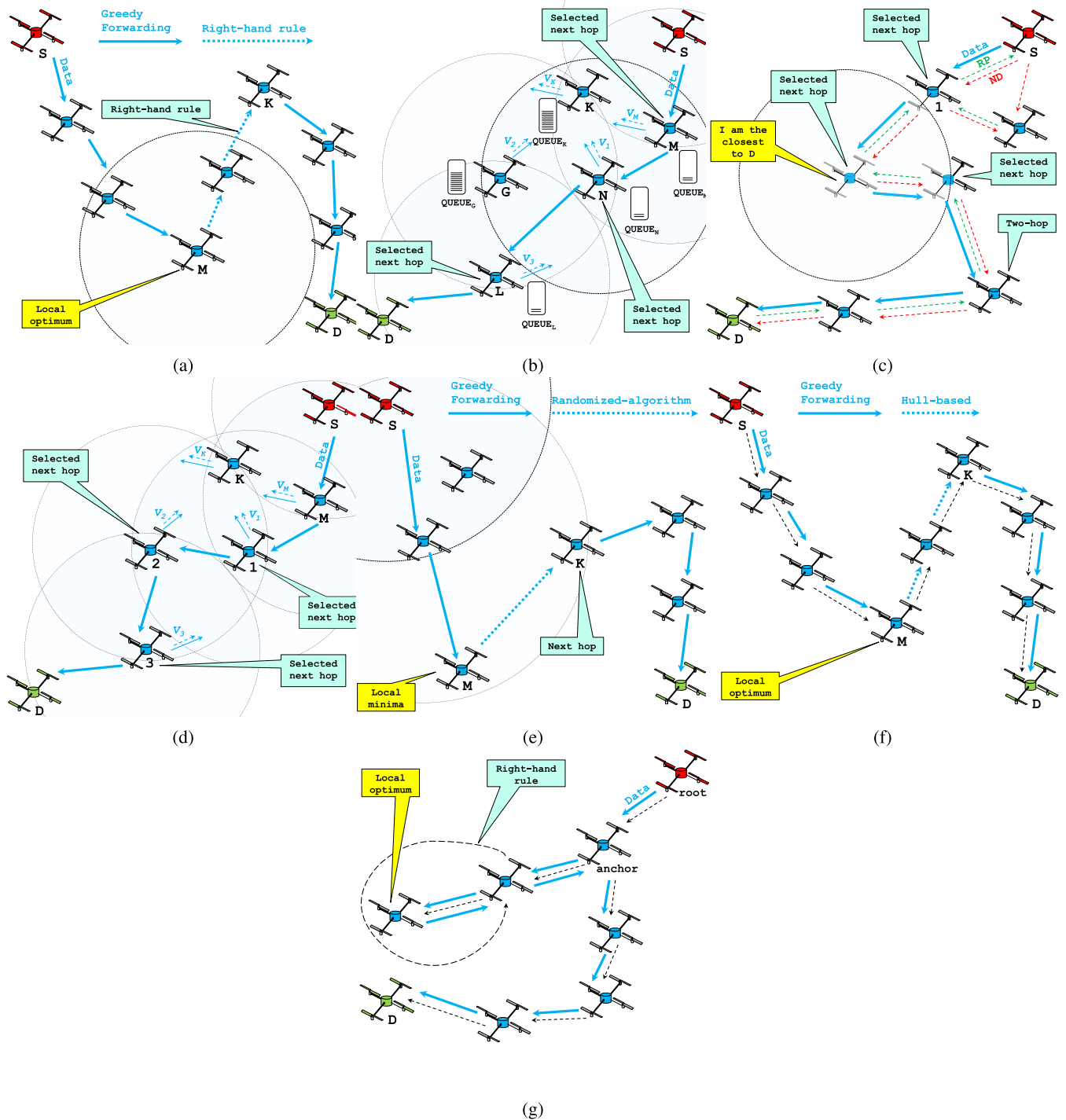
Generally, when a FANET network becomes almost connected and the position of the destination is known, the data packets are always forwarded to UAVs that allow minimizing the number of hops and the distance to the target destination, thus employing the greedy forwarding technique. Furthermore, this technique also aims to reduce the delay of delivery. Nevertheless, the connectedness of FANET is not constant all time since UAVs are highly mobile, which makes the greedy forwarding unreliable when it is misused resulting in important packet losses.

GPSR (Greedy Perimeter Stateless Routing) [214] is a greedy-based routing protocol consisting of two modes:

(i) Greedy Forwarding and (ii) Perimeter Forwarding. For the right functionality of the first mode, the position of the destination node is assumed to be known and the node with the closest position to the destination is selected as the next hop of the data packet. Due to the mobility nature of the network, the greedy forwarding mode can fail at any time when the selected next hop is the closest one to the destination and no nodes in the neighboring. In this case, the second mode can take over and it forwards the packets based on the right-hand rule until the network becomes progressively connected and returns to greedy mode. GPSR has been adopted in a densely deployed FANET, such as in [215]. For instance in Figure 22(a), UAV  $S$  starts using the greedy forwarding during the data delivery to transmit a data packet to UAV  $D$ . When a local optimum is detected (*i.e.*, at the level of UAV  $M$ ), GPSR starts applying the right-hand rule and it switches on the greedy mode at the level of UAV  $K$  until that the data packet will be delivered to UAV  $D$ .

GLSR (Geographic Load Share Routing) [216] is an enhanced version of the routing protocol GPSR [214] in order to be adapted to FANETs. GLSR exploits all the possible routing paths between the communicating UAVs. The data packets are sent to the UAVs that allow progressing to the target destination. To do so, a distance advance metric is calculated for each UAV neighbor in order to define the best routing paths towards the destination. Moreover, each UAV maintains a queue for packets to send in which its degree of filling is also considered during the selection of the appropriate path. The selection of an adequate forwarder in GLSR is exemplified in Figure 22(b). UAV  $S$  checks in its neighboring to find, if possible, the UAV that has and the lowest queuing delay and the highest speed advance towards UAV  $D$ . As a result, UAV  $M$  satisfies all the previously mentioned characteristics and it is selected to forward the data packet. The same process is repeated at each hop until the data packet will be delivered to UAV  $D$ .





**FIGURE 22.** Greedy-based routing protocols. (a) Mechanism of GPSR. (b) Mechanism of GLSR. (c) Mechanism of MPGR. (d) Mechanism of GPMOR. (e) Mechanism of GRG. (f) Mechanism of GHG. (g) Mechanism of GDSTR.

MPGR (Mobility Prediction based Geographic Routing) [217] is a FANET position-based routing protocol based on the greedy forwarding technique. A mobility prediction method combined with the Gaussian distribution function and all based on GPSR (Greedy Perimeter Stateless Routing) [214]. This can minimize the overhead and participate in

the selection of the most adequate next hop, and thus a stable routing path between the communicating UAVs. MPGR uses an on-demand position sharing technique by broadcasting a Neighbor Discovery packet (ND). Each ND packet contains the delivery mode (e.g., perimeter or greedy) and the position of the destination. Each neighboring UAV replies by its

respective neighbor list so as to allow the UAV sender to construct its own neighbor table. As exemplified in Figure 22(c), If UAV  $S$  wants to communicate with UAV  $D$ , it broadcasts an ND packet to discover the available next hops and to select the most adequate based on the intercepted Reply Packet (RP). To avoid any link failures, MPGR predicts the position of the next UAVs at time  $t_n$  based on their mobility information at  $t_{n-1}$ . Thus, MPGR can select next forwarding UAV more precisely. In the case when a forwarder UAV detects that it is the closest UAV to UAV  $D$ , the greedy mode fails and the perimeter mode is used instead. The distance between each two-hop neighbor and UAV  $D$  is calculated and the most adequate one is selected to forward the data packet to UAV  $D$ .

GPMOR (Geographic Position Mobility Oriented Routing) [218] is a greedy-based routing protocol devoted for FANETs. In GPMOR, each UAV is able to know its own position and the positions of the neighboring UAVs based on the embedded GPS and the periodical exchange of beacons, respectively. Based on this information, GPMOR can estimate the new positions of the neighboring UAVs during a period of time. Moreover, the neighbor tables are created and updated accurately allowing the forwarder UAVs to be able to select the optimal next hops towards the target destination. GPMOR makes the selection using the adopted prediction technique (*c.f.*, Figure 22(d)). When UAV  $S$  wants to send a data packet to UAV  $D$ , it selects UAV  $M$  as the next hop because its future movement is towards UAV  $D$ . Nevertheless, UAV  $K$  cannot be considered as the next forwarder since it can move away from the communication range of UAV  $S$ , thus avoiding the packet losses. Once UAV  $D$  will be in the range of a forwarder UAV, the data packet is immediately delivered to it.

GRG (Greedy-Random-Greedy) [219] is another greedy-based routing protocol using two different schemes according to the situation of the network. Firstly, the greedy forwarding technique is applied during the data delivery until a local minimum is found. Secondly, a randomized algorithm is used as a recovery strategy trying to randomly find from a subset of the current neighbors a next hop towards the destination. This can be done by using several strategies, such as the random walk on the surface or the region-limited random walk. As shown in Figure 22(e), UAV  $S$  assumes that the position of UAV  $D$  and those of the neighbors are all known based on a location service and the periodical exchange of Hello packets including the positions, respectively. The greedy forwarding is applied to transmit the data packet across the network through the closest UAVs towards UAV  $D$ . When a local minimum is found (*i.e.*, UAV  $M$  has no neighbors and it is the closest to UAV  $D$ ), the randomized algorithm is used to find the appropriate next hop (*i.e.*, UAV  $K$ ). Then, the greedy forwarding is re-applied to forwards the data packet to UAV  $D$ .

GHG (Greedy-Hull-Greedy) [220] is 3D routing protocol based on the hull to avoid a local optimum problem. As a backup mechanism, instead of planarization, a PUDT (Partial Unit Delaunay Triangulation) protocol is adopted to divide the network area into a set of closed sub-spaces

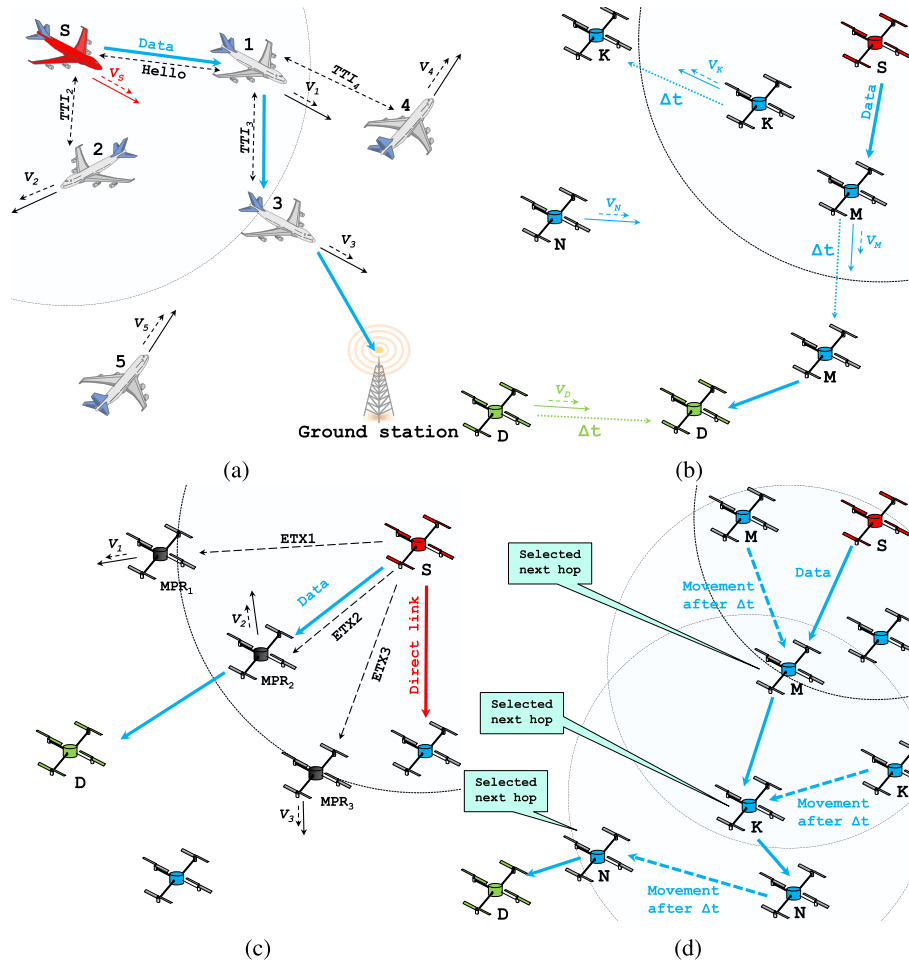
to minimize the local backup process. By applying GHG, a frequent alteration between greedy forwarding and hull-based local optimum recovery is carried out. In the example shown in Figure 22(f), the greedy forwarding is applied to send a data packet between UAV  $S$  and UAV  $D$ . In the local optimum UAV  $M$ , hull-based routing delivers the data packet from UAV  $M$  to UAV  $K$  where the greedy forwarding is re-applied (*i.e.*, UAV  $K$  is much closer to UAV  $D$  than UAV  $M$ ) until that the data packet will be delivered to UAV  $D$ .

GDSTR (Greedy Distributed Spanning Tree Routing) [221] is a greedy-based routing protocol using a spanning tree as a replacement routing topology on the contrary of classical geographic routing adopting a planar graph. Furthermore, GDSTR uses two-hops neighbor information during the greedy forwarding to minimize the local optimum, and collecting the geographical coordinates of UAVs using two 2D convex hulls. To select a direction that is the most adequate to make progress towards the destination, each UAV maintains a set of zones covered by the sub-tree below each of its tree of neighbors. In the scenario depicted in Figure 22(g), when a UAV *root* wants to establish a communication with UAV  $D$ , the data packet is firstly sent through the tree until it gets the routing subtree. The first transited UAV belonging to the subtree is called an anchor node. Since the root is present in each subtree, the packet reaches the root and it finds itself as incommunicable (*i.e.*, local optimum). To avoid this situation, the right-hand rule is used to deliver the data packet to UAV  $D$ .

### 3) PREDICTIVE

The communication between UAVs is not stable and frequently disconnects due to the highly dynamic mobility of UAVs. To adapt to this situation, there are some solutions that can be derived from the predictable movements of UAVs to develop routing protocols dedicated to this scenario. This can provide alternatives to predict how long wireless links would last between UAVs. However, sometimes a full routing path to the target destination is needed for the data delivery, which is considered as a complex technique to be implemented since its connectivity expiration has to be predicted. Furthermore, the complexity becomes obvious, particularly when FANETs adopt a 3D topology, which also brings new difficulties.

AeroRP (Aeronautical Routing Protocol) [222], [223] is a predictive routing protocol dedicated to aeronautical networks consisting of aircraft (fast flying vehicles). The main objective of AeroRP is to connect aircraft with a ground station. The first step of AeroRP is to discover the neighboring aircraft by collecting their speeds, velocities, and positions. Based on this information that is updated periodically using Hello packets, a metric called Time To Intercept (TTI) is computed for each neighboring aircraft to select the one that stays within the communication range of the current node for a reasonable amount of time. When an Aircraft  $S$  wants to communicate with the ground station, a selection process is engaged among the neighboring aircraft 1, 2, and 3.  $S$  calculates TTI for all neighbors and the one obtaining the



**FIGURE 23. Predictive-based routing protocols. (a) Mechanism of AeroRP. (b) Mechanism of GRAA. (c) Mechanism of P-OLSR. (d) Mechanism of ABPP.**

lowest TTI (*i.e.*, Aircraft 3) is selected to forward the data packet (*c.f.*, Figure 23(a)). The same process is repeated until the data packet will be delivered to the ground station.

GRAA (Geographic Routing protocol for Aircraft Ad hoc Network) [224] is a position-based routing protocol taking into account the mobility prediction of UAVs during the data delivery. GRAA is based on GPSR [214] in which before each data transmission, the forwarder UAV considers the positions, the speeds, and the velocities of all neighbors and the destination as well. To avoid any packet losses, all the next hops before reaching the destination are calculated using the same process. Figure 23(b) shows an example, when UAV *S* selects the appropriate next hop based on the mobility prediction of its neighbors (*i.e.*, UAV *M* and UAV *K*) relative to the movement of the destination UAV *D*. Indeed, UAV *S* estimates the future position of UAV *D* after a period of time  $\delta t$  using its current position and speed. The same estimation is carried out for all neighbors based on the same time  $\delta t$ . The UAV with the adequate calculated future position to that of UAV *D* will be selected as a next hop. It is clearly shown that UAV *M* will be much closer to UAV *D* than UAV *K* after

$\delta t$ , and thus it is selected as the next hop. Nevertheless, when there are no neighboring UAVs, UAV *M* continues to carry the data packet until it gets UAV *D*.

P-OLSR (Predictive-Optimized Link State Routing Protocol) [225] is a routing variant of OLSR [155], which is dedicated to FANETS. As indicated by its name, it takes advantage of the positions of UAVs so as to predict the robustness of the links between UAVs and to select the one providing the smallest degree of packet losses. To do so, the exchanged Hello messages do not only include the link state information, but also the mobility information of UAVs (*i.e.*, positions, speeds, and velocities). This allows to estimate a metric called Expected Transmission Count (ETX) to define both how long the UAV stays within range and how the links evolve, thus reducing the intermittent connectivity. When a UAV *S* has a data packet to send, it selects the most adequate MPR UAV (*i.e.*, *MPR*<sub>2</sub> in Figure 23(c)). This can be done based on the calculated ETX metric of all MPRs in range by considering the relative speeds between UAV *S* and MPRs. Consequently, the number of MPRs is reduced significantly by only leaving those having a good connectivity.

TABLE 13. Comparative study of position-based routing protocols.

			Route	Density	Complexity	Advantage	Inconvenient
Reactive	ARPAM	Ref. [210]	On demand	High	Medium	Reduces the delay and link failures.	Supports only low mobility.
	RGR	Ref. [211]	On demand	High	Medium	Uses efficient maintenance strategy.	Does not predict next hops positions.
	MUDOR	Ref. [213]	On demand	High	Medium	Reduces flooding.	Does not support low densities.
Greedy	GPSR	Ref. [215]	Dynamic	High	Medium	Minimizes delays and hops.	Does not support link failures.
	GLSR	Ref. [216]	Dynamic	Medium	Medium	Performs load balancing among UAVs.	Does not consider stability of links.
	MPGR	Ref. [217]	On demand	High	High	Considers stability to enhance delivery.	Neglects the link expiration time.
	GPMOR	Ref. [218]	Dynamic	Medium	Medium	Selects relays using predictions.	Does not consider fragmentations.
	GRG	Ref. [219]	Dynamic	High	Medium	Supports high mobility of nodes.	Does not consider realistic scenarios.
	GHG	Ref. [220]	Dynamic	High	Medium	Supports 3D mobility.	Suffers from high delays.
Predictive	GDSTR	Ref. [221]	Dynamic	High	High	Enhances the greedy forwarding.	Supposes static topology.
	AeroRP	Ref. [223]	Dynamic	Low	Low	Enhances delivery ratio.	Increases delivery delays.
	GRAA	Ref. [224]	Dynamic	Low	Low	Predicts future locations of nodes.	Assumes random UAV motion.
	P-OLSR	Ref. [225]	Dynamic	Low	High	Uses positions to handle the high mobility.	Any recovery strategy is used
	ABPP	Ref. [226]	Dynamic	High	Medium	Enhances overhead and delivery ratio.	Requires dense networks.

ABPP (Adaptive Beacon Position Prediction) [226] is a prediction-based routing protocol dedicated for FANETs. ABPP exploits the position history of UAVs using the weighted linear regression model. Moreover, ABPP includes a fuzzy controller to adaptively adjust the frequency of beacon advertisement in which the prediction error degree and the beacon interval are the input and the output, respectively. A geographical routing protocol inspired by GPSR [214] is adopted by ABPP, which records the time information and position of the neighboring UAVs. In the example depicted in Figure 23(d), UAV  $S$  selects the closest the neighbor UAV or the UAV that will be the closest one after a period of time  $\delta t$ . UAVs  $M$ ,  $K$ ,  $N$ , are the successions of selected next hops to reach the target destination UAV  $D$ .

TABLE 13 presents a summarize of all discussed sub-categories of the position-based routing protocols.

#### H. DELAY TOLERANT NETWORKS

When the network is severely fragmented, UAVs have to carry the packets in order to avoid losing them by the SCF technique. This is done until that the network becomes partially connected (*i.e.*, meeting other UAVs) using different metrics and techniques.

##### 1) DETERMINISTIC

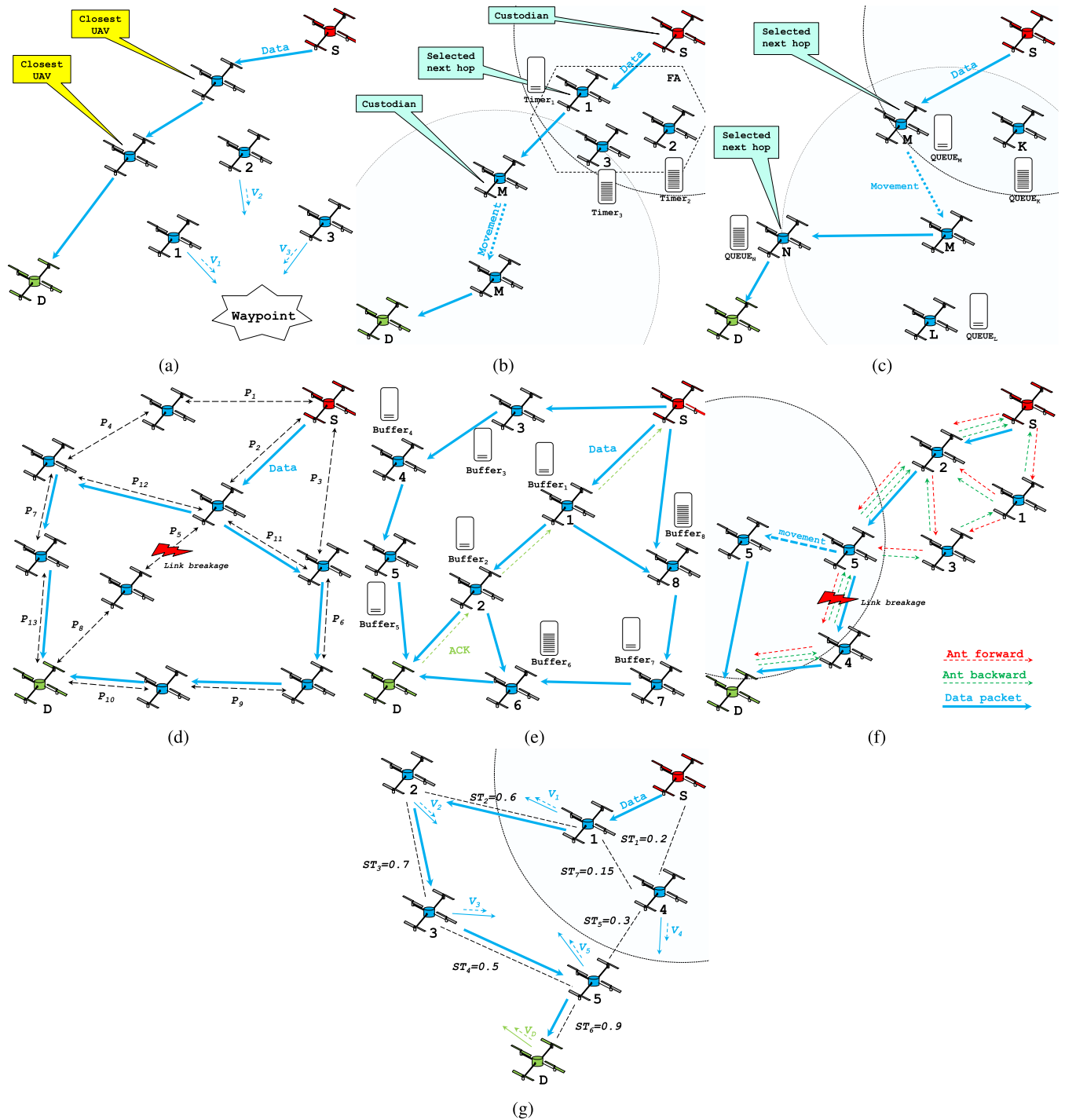
This kind of protocols is applied in sparsely connected networks, such as FANETs where connectivity situations can be easily predicted, and especially when UAVs do not adopt random mobility models.

USMP (UAV Search Mission Protocol) [227] is a deterministic routing protocol dedicated to FANETs. USMP is based on the mechanism of GPSR [214] considering two features: (i) location update and (ii) waypoint conflict. In the first feature, USMP passes explicitly the messages to the neighboring UAVs and it uses GPSR to forward them. As for the second feature, USMP selects a UAV having a great probability to arrive at the waypoint first by calculating a specific metric. Figure 24(a) depicts an example where UAV  $S$  tries to communicate with UAV  $D$  by applying USMP. To use GPSR, UAVs exchange among themselves their positions in order to

be able to select the next hops correctly. As for the waypoint conflict, it occurs when at least two UAVs move towards the same location and collide (*i.e.*, UAV 1, 2, and 3). A metric called Expected Arrivals Rule (EAR) is calculated for each UAV involved in the conflict, which permits to select the UAV that has the highest EAR value. This allows to minimize the amount of repetitive searching by prohibiting UAVs from moving to the same waypoint at the same time.

LAROD (Location Aware Routing for Opportunistic Delay tolerant network) [228] is a delay tolerant routing protocol dedicated to FANETs. LAROD combines two different techniques used interchangeably according to the situation of the network: (i) the SCF technique and (ii) the greedy forwarding technique. The first technique is used when the network is intermittently connected, where the custodian (*i.e.*, the UAV holding the packet) continues to broadcast the data packet until a next forwarder providing a minimum progress towards the destination is found. However, the second technique is used when other UAVs nearby are within range of the custodian that create the Forwarding Area (FA). To limit the broadcast of the packet and its indefinite delivering over the network, a mechanism of overhearing is applied between the intermediate UAVs and the destination responds with an acknowledgment. To better explain LAROD, we consider the example of Figure 24(b). The custodian UAV  $S$  broadcasts the data packet to the FA (*i.e.*, some eligible UAVs that are moving towards UAV  $D$ ). After the intercepting the data packet, the UAVs 1, 2, and 3 set a timer where the first UAV having its timer expired is considered the selected next custodian. When overhearing a UAV disseminating a data packet, the neighboring UAVs withdraw their copy of the packet. In the case when the custodian has no neighboring UAVs (*e.g.*, UAV  $M$ ), the packet is broadcasted periodically until a next hop will be found. Otherwise, the custodian holds the packet until it will be delivered to the target destination.

FGQPA (Fountain-code based Greedy Queue and Position Assisted) [229] as a delay tolerant network routing protocol, it has an objective to reduce the transmission delay within a FANET. To do so, FGQPA considers two different schemes: (i) a Power Allocation and Routing (PAR) scheme and



**FIGURE 24.** DTN-based routing protocols. (a) Mechanism of USMP. (b) Mechanism of LAROD. (c) Mechanism of FGQA. (d) Mechanism of SEPR. (e) Mechanism of RAPID. (f) Mechanism of AC. (g) Mechanism of TENSUR.

(ii) a nearest span scheme. The first scheme aims to transit the data packets through UAVs having a low queue backlog, thus, all the queues of UAVs will be well-regulated and the delay will be reduced significantly. The second scheme aims to forward the packets towards the destination while the transmission delay is even shorter. In addition, a fountain code scheme is added to make the end-to-end communication

more reliable despite a high loss rate. In Figure 24(c), a data packet will be carried by UAV S until an adequate next hop is found. Each UAV maintains a local queue and is able to define its own geographical position, which can be all used as a routing metric. If there are at least two possible next hop neighbors (*i.e.*, UAVs M and K), FGQA firstly calculates their queues length and their distances that separate

them from the destination, which are all shared through Hello packets. UAV  $M$  will be selected as the next hop, since it has a smaller queue and it is the closest to the destination. The same process is repeated until the data packet will be delivered to UAV  $D$ .

## 2) STOCHASTIC

When UAVs adopt a random mobility, it will not be possible to predict their future positions or directions, and thus impossible to select next hops. To avoid this situation, stochastic protocols broadcast data packets to all neighbors ensuring the gradual deliverance to the target destination.

SEPR (Shortest Expected Path Routing) [230] is a stochastic-based routing protocol based on the link probability estimated from the history of data, which can be easily adapted to FANETs. SEPR is similar to a classical link state routing protocol in the way how UAVs update their routing tables. UAVs exchange the link probability update messages along the shortest path to the destination named effective path length (EPL). When a UAV receives a smaller EPL value from a neighboring UAV, it modifies locally its EPL value meaning a higher probability transmission. EPL is used as a metric to make a routing decision and to forward the messages to the appropriate UAV. To enhance reliability and minimize delays, SEPR can forward the same message to multiple UAVs. In the scenario shown in Figure 24(d), there is a network represented as a graph (*i.e.*, nodes (UAVs) and weighted edges (links with probabilities)). Each weight represents a connection existence probability ( $0 \leq P_i \leq 1$ ). When a communication needs to be engaged between UAVs  $S$  and  $D$ , the data packet is delivered over the shortest path towards  $D$  based on the EPL metric calculated between UAVs. However, when a link breakage occurs on the link with the probability  $P_5$ , multiple copies of the data packet are delivered through multiple paths to UAV  $D$ .

RAPID (Resource Allocation Protocol for Intentional Delay Tolerant Networks) [231] is a routing protocol handling the DTN routing problem by considering buffer constraints, bandwidth, and resource allocation. RAPID can be used in FANETs by assuming several hypotheses, such as the limited storage capacity and bandwidth for all UAVs except the destination that has unlimited buffer space to receive all possible packets. Two UAVs can communicate with each other when they are within the transmission of each other while storing a copy of each received packet. The message is flooded across the network until it will be delivered to the target destination that replies with an acknowledgment. When a data packet should be sent to UAV  $D$ , UAV  $S$  broadcasts it over the network (*c.f.*, Figure 24(e)). Each received data packet will be stored in the buffer of each transited UAV. When the data packet reaches UAV  $D$ , an acknowledgment (ACK) is propagated back to UAV  $S$  through the routing path composed of UAVs having the least filled buffers and sufficient bandwidth. This path will be re-used for other data packet transmissions.

AC (Ant Colony-based routing) [232] is a bio-inspired routing protocol for DTN FANETs. AC is based on ant foraging behavior in order to regulate the exploration-exploitation capacity. Exploration is defined as the capacity to search for all possible routes while Exploitation is the technique to focus on a promising group of solutions. This pivotal architecture results in ant pheromone and heuristic information. To calculate the heuristic information, an approximate reasoning fuzzy interference based on the crow density (CD) and the relative velocity direction (RVD), which are estimated with a simple computational cost. In highly dynamic networks, AC should explore new routes and every UAV in range is considered as an opportunity to forward the messages. Figure 24(f) shows how AC can find a routing path to the target destination. UAV  $S$  broadcasts forward ants across the network and backward ants are forwarded back to UAV  $S$  while updating the pheromone value in the routing tables of each transited UAV to plot the routing path to UAV  $D$ . When a link failure occurs, the custodian UAV (*i.e.*, UAV  $M$ ) carries the data packet until an appropriate UAV is found to relay it or it will be carried until it will be delivered to UAV  $D$ .

## 3) SOCIAL NETWORKS

This concept can be used when the mobility of UAVs and their behaviors are known. This allows to have an accurate prediction of the future positions and directions of UAVs, which can be used to select a set of intermediate UAVs to forward the data packets. However, this kind of routing protocols is relatively new and it is not widely deployed in FANETs.

TENSR (Tactical Edge Network Social Routing) [233] is a social-based routing protocol exploiting mobility plans and broadcasting social tie information. TENSR can be applied to FANETs since both kinds of information are combined to make routing decisions. The mobility plans of each UAV can be defined beforehand so that at each time the positions of all UAVs can be estimated. This information is disseminated to all UAVs through a dedicated channel, which allows all UAVs to know the positions of each other. To study the probability that two UAVs stay in range of each other, the network is modeled as a social graph composed of vertices (UAVs) and weighted edges defining the social tie strengths (*i.e.*, the frequency of encounters) between each pair of UAVs. In TENSR, the routing process consists of two main parts: (i) exchange of routing table and (ii) route selection. The aim of the first part is that it provides all UAVs with the required information from which UAVs can estimate the adjacency probabilities (*i.e.*, social ties). These probabilities are then used in the second part to select the appropriate route for data delivery. After calculating all social ties (ST), UAV  $S$  forwards the data packet through a set of links having a high STs (*c.f.*, Figure 24(g)).

A summarize of all DTN routing protocols is presented (*see* TABLE 14).

TABLE 14. Comparative study of DTN routing protocols.

			Route	Density	Complexity	Advantage	Inconvenient
DTN	USMP	Ref. [227]	Dynamic	Low	Medium	Enhances the delivery ratio.	Increases delivery delays.
	LAROD	Ref. [228]	Dynamic	Low	Low	Low overhead and energy consumption.	Does not assume high mobility.
	FGQPA	Ref. [229]	Dynamic	High	High	Reduces delivery delays and packet losses.	Does not use recovery process.
	SEPR	Ref. [230]	Dynamic	Low	Medium	Considers sparsely connected networks.	Introduces high delays.
	RAPID	Ref. [231]	Dynamic	Low	Low	Effectively reduces delay and overhead.	Does not support 3D scenarios.
	AC	Ref. [232]	On demand	High	High	Enhances the delivery ratio.	Introduces high delay and overhead.
TENSR	Ref. [233]	Dynamic	Medium	Medium	Enhances delivery delay and ratio.	Specific use case and energy overuse.	

TABLE 15. Global comparative study of FANET routing protocols.

			Routing strategies												Requirements			Features					Methods of validation		
			SCF	GF	PR	DP	CL	LST	HR	MI	EE	STA	SC	BR	GPS	LS	GRS	MM	BD	OH	LT	RU	TST	SM	MMD
Topology	OLSR	Ref. [155]	x	x	x	x	x	√	x	x	x	x	x	x	No	No	Sometimes	High	High	Medium	Low	Periodically	Simulation	NS-2	RWP
	D-OLSR	Ref. [163]	x	x	x	x	x	√	x	x	x	x	x	x	No	No	Yes	High	High	Low	Medium	Periodically	Simulation	OPNET	RW
	M-OLSR	Ref. [164]	x	x	x	x	x	√	x	x	√	x	x	x	Yes	No	No	Medium	High	High	Low	Periodically	Simulation	QualNet	RWP
	CE-OLSR	Ref. [165]	x	x	√	x	x	√	x	x	√	x	x	x	Yes	No	No	High	Medium	High	Medium	On-demand	Simulation	N/A	RWP
	DSDV	Ref. [166]	x	x	x	x	x	√	x	x	x	x	x	x	No	No	No	Medium	Low	Medium	High	Periodically	Simulation	NS-2	RW
	TBRPF	Ref. [169]	x	x	x	x	x	√	x	x	x	x	x	x	No	No	No	Low	Medium	Low	Low	Periodically	Simulation	NS-3	RWP
	BATMAN	Ref. [172]	x	x	x	x	x	√	x	x	x	x	x	x	No	No	No	Medium	Medium	High	Medium	Periodically	TestBed	N/A	FP
	AODV	Ref. [176]	x	x	x	√	x	x	x	x	x	x	x	x	No	No	No	Medium	High	High	High	On-demand	Simulation	NS-2	RWP
	TS-AODV	Ref. [177]	x	x	x	√	x	x	x	x	x	x	x	x	No	No	Sometimes	Medium	Low	Low	Medium	On-demand	Simulation	NS-2	RWP
	M-AODV	Ref. [178]	x	x	x	√	x	x	x	x	x	x	x	√	No	No	No	High	Medium	Medium	Medium	On-demand	Simulation	NS-2	RWP
	DSR	Ref. [174]	x	x	x	√	x	x	x	x	x	x	x	x	No	No	Sometimes	High	High	High	High	On-demand	Simulation	NS-2	RW
	HWMP	Ref. [162]	x	x	x	√	x	√	x	x	x	x	x	x	No	No	No	High	Low	Low	Medium	Hybrid	Simulation	NS-3	GM
	ZRP	Ref. [181]	x	x	x	√	√	x	x	x	x	x	x	x	Yes	No	No	Medium	Medium	High	Low	Hybrid	Simulation	NS-2	RWP
	SHARP	Ref. [182]	x	x	x	√	√	x	x	x	x	x	x	x	No	No	No	Low	Medium	Low	Medium	Hybrid	Simulation	OPNET	RWP
	TORA	Ref. [183]	x	x	x	√	√	x	x	x	x	x	x	x	No	No	No	Medium	High	Low	Medium	Hybrid	Simulation	NS-3	E-GM
MLHR	Ref. [37]	x	x	x	√	√	x	x	x	x	√	x	x	No	No	No	Medium	Medium	High	Medium	Dynamic	Simulation	NS-2	RWP	
LCAD	Ref. [184]	√	x	x	√	√	x	x	x	x	√	x	x	Yes	Yes	Yes	Medium	Medium	Low	High	Dynamic	Simulation	NS-2	FP	
DCR	Ref. [37]	x	x	x	√	√	x	x	x	x	√	x	√	No	No	Sometimes	Medium	Low	Medium	High	Dynamic	Simulation	NS-2	RWP	
Secure	SUANET	Ref. [185]	x	x	x	√	x	x	x	x	x	√	x	Yes	No	Yes	Medium	High	High	Medium	On-demand	TestBed	N/A	FP	
	PASER	Ref. [186]	x	x	x	√	x	x	x	x	x	√	x	Yes	No	Yes	High	High	High	Low	On-demand	Simulation	OMNeT++	FP	
	SUAP	Ref. [187]	x	x	x	√	x	x	x	x	x	√	x	Yes	No	Yes	High	High	High	High	On-demand	TestBed	N/A	FP	
	AODV-SEC	Ref. [188]	x	x	x	√	x	x	x	x	x	√	x	No	No	No	Medium	High	High	High	On-demand	Simulation	NS-2	N/A	
SRPU	Ref. [189]	x	x	x	√	x	x	x	x	x	√	x	No	No	Yes	Medium	High	High	High	On demand	TestBed	N/A	FP		
Bio	APAR	Ref. [191]	x	x	x	√	x	x	x	x	√	x	x	Yes	No	Yes	High	High	High	Medium	On-demand	Simulation	NS-2	RWP	
	BeeAdhoc	Ref. [192]	x	x	x	√	x	x	x	x	x	x	x	Yes	No	Yes	High	High	High	Medium	On-demand	Simulation	NS-2	RWP	
	POSANT	Ref. [193]	x	√	x	x	x	x	x	√	x	x	x	Yes	No	No	High	Medium	Medium	Low	Dynamic	Simulation	VC++	N/A	
Hierarchical	CA	Ref. [194]	x	x	x	√	x	√	x	x	x	x	x	Yes	Yes	Yes	High	High	High	Low	Dynamic	Simulation	N/A	N/A	
	MPCA	Ref. [195]	x	x	x	√	x	√	x	x	x	x	x	Yes	Yes	No	High	Medium	Medium	High	Dynamic	Simulation	NS-2	N/A	
	EHSR	Ref. [196]	x	x	x	√	x	√	x	x	x	x	x	No	Yes	No	High	Medium	Medium	Medium	Dynamic	Simulation	GlomoSim	RWP	
	MMT	Ref. [197]	x	x	√	x	√	x	√	x	x	x	x	Yes	Yes	No	Medium	Medium	High	Low	Dynamic	Simulation	N/A	N/A	
	DTM	Ref. [198]	x	x	√	x	√	x	√	x	x	x	x	Yes	No	No	High	High	High	High	On-demand	Simulation	NS-2	N/A	
Energy	CBLADSR	Ref. [199]	x	x	x	√	√	x	x	√	√	x	x	Yes	No	No	High	High	High	Medium	On-demand	Simulation	OPNET	ECR	
	EALC	Ref. [200]	x	x	x	√	x	√	x	√	x	x	x	Yes	Yes	Yes	Medium	Medium	High	Medium	Dynamic	Simulation	MATLAB	PSMM	
	EPLA	Ref. [201]	x	√	x	x	x	√	x	√	x	x	x	Yes	Yes	Yes	High	Low	Low	High	Dynamic	Simulation	MATLAB	N/A	
	IMRL	Ref. [202]	x	x	√	x	√	x	√	x	√	x	x	Yes	Yes	Yes	High	High	High	Low	Dynamic	Simulation	MATLAB	SRCM	
Hetero	CRUV	Ref. [203]	√	√	x	x	x	x	x	x	x	x	x	Yes	Yes	No	Medium	Medium	Low	Low	Dynamic	Simulation	NS-2	RW	
	XLRGo	Ref. [206]	x	√	x	x	x	x	x	x	x	x	x	Yes	Yes	Yes	Medium	High	High	Low	Dynamic	Simulation	OMNeT++	RWP	
	UVAR	Ref. [207]	√	√	x	x	x	x	x	x	x	x	x	Yes	Yes	No	Medium	Medium	Low	Low	Dynamic	Simulation	NS-2	RW	
	DFRM	Ref. [208]	x	√	√	x	x	√	x	√	x	x	x	Yes	Yes	Yes	High	Medium	Medium	Low	Dynamic	Simulation	NS-2	RWP	
Position	ARFAM	Ref. [210]	x	x	x	√	x	x	x	x	x	x	x	Yes	Yes	No	Medium	High	High	Low	On-demand	Simulation	OPNET	RWP	
	RGR	Ref. [211]	x	√	√	√	x	x	√	x	x	x	x	Yes	Yes	No	Medium	High	High	Medium	On-demand	Simulation	OPNET	RWP	
	MUDOR	Ref. [213]	x	x	√	x	x	x	√	x	x	x	x	Yes	Yes	No	Medium	High	High	Medium	On-demand	Simulation	JAVA	RW	
	GPSR	Ref. [215]	x	√	x	x	x	x	x	x	x	x	x	Yes	Yes	No	High	Medium	Medium	Low	Dynamic	Simulation	NS-2	RPGM	
	GLSR	Ref. [216]	x	√	x	x	x	x	x	x	x	x	x	Yes	Yes	Yes	Low	Medium	Medium	High	Dynamic	Simulation	OMNeT++	RW	
	MPGR	Ref. [217]	x	√	√	x	x	x	√	x	x	x	x	Yes	Yes	No	Medium	Medium	High	Low	Dynamic	Simulation	NS-2	GM	
	GPJOR	Ref. [218]	x	√	√	x	x	x	√	x	x	x	x	Yes	Yes	No	Medium	Medium	High	Low	Dynamic	Simulation	NS-2	GM	
	GRG	Ref. [219]	x	√	x	x	x	x	x	x	x	x	x	Yes	No	No	Low	Medium	Low	Low	Dynamic	Simulation	JAVA	RW	
	GHG	Ref. [220]	x	√	x	x	x	x	x	x	x	x	x	Yes	Yes	No	Low	Medium	Low	Low	Dynamic	Simulation	N/A	RW	
	GDSTR	Ref. [221]	x	√	x	x	√	x	x	x	√	x	x	Yes	Yes	No	Medium	Medium	Low	Low	Dynamic	TestBed	TOSSIM	RWP	
	AeroRP	Ref. [223]	√	x	√	x	x	x	√	x	x	x	x	Yes	Yes	Yes	High	Medium	Low	High	Dynamic	Simulation	NS-3	RWP	
GRAA	Ref. [224]	√	x	√	x	x	x	√	x	x	x	x	Yes	Yes	Yes	High	Medium	Low	High	Dynamic	Simulation	QualNet	RWP		
P-OLSR	Ref. [225]	x	x	√	x	x	√	x	√	x	x	x	Yes	Yes	Yes	High	High	High	High	Periodically	TestBed	N/A	FP		
ABPP	Ref. [226]	x	√	√	x	x	x	√	x	x	x	x	Yes	Yes	No	Low	Medium	Medium	Low	Dynamic	Simulation	NS-3	RWP		
DTN	USMP	Ref. [227]	√	√	x	x	x	x	x	x	x	x	x	Yes	Yes	No	High	Low	Low	High	Dynamic	Simulation	OPNET	PSMM	
	LAROD	Ref. [228]	√	√	x	x	x	x	x	x	x	x	x	Yes	Yes	No	Medium	Medium	High	High	Dynamic	Simulation	NS-2	DFR	
	FGQPA	Ref. [229]	√	√	x	x	x	x	√	x	x	x	x	Yes	Yes	Yes	Medium	Medium	Medium	Low	Dynamic	Simulation	NS-3	ST	
	SEPR	Ref. [230]	√	x	√	x	x	√	x	x	x	√	x	√	Yes	Yes	No	High	Medium	Medium	High	Dynamic	Simulation	CSMM	MG
	RAPID	Ref. [231]	√	x	x	x	x	x	x	x	x	√	x	√	Yes	Yes	No	High	Low	Low	High	Dynamic	TestBed	DieselNet	FP
	AC	Ref. [232]	√	x	x	√	x	x	√	x	x	x	x	Yes	No	No	High	High	High	Low	On-demand	Simulation	ONE	RWP	
	TENSR	Ref. [233]	√	x	√	x	x	x	√	x	x	x	x	Yes	Yes	No	Medium	High	Medium	Medium	Periodically	Simulation	NS-3	PRS	

VI. A GLOBAL COMPARATIVE STUDY

Two crucial comparative studies are carried out in the context of this survey. First, all discussed FANET routing protocols are compared between each other using various criteria to differentiate between the routing protocols and to have an overview on which routing protocol should be adopted in a given situation. Second, the different simulation tools used as a verification methodology are studied and statistically discussed.

A. COMPARISON OF FANET ROUTING PROTOCOLS

As illustrated in TABLE 15, the eight categories of FANET routing protocols are compared based on multiple parameters, such as the routing strategies, the requirements, the features, and the methods of validation. The different routing strategies are those described in Section IV. Three crucial requirements are studied, which are frequently used by routing protocols, such as the GPS to calculate the geographical positions, the location service (LS) to estimate the position of each

UAV and sometimes it is used to get the motion information of UAVs, and the ground base station (GBS) that is used in different scenarios, such as the transmission or the reception of certain information, the coverage extension, or even the control of the mobility.

Some popular features extracted from both the mechanisms and the experiment outputs of the routing protocols, such as the required memory (MM) to make calculation and processing, the used bandwidth (BD) during the routing process, the average overhead (OH) of all data transmissions, the latency (LT) which is the average time needed for a data transmission, and the technique used during the route update (RU). Two different methods of validation (TST) are used: (i) Simulation and (ii) TestBed. The used simulation tool or the TestBed environment (SM) and the applied mobility model (MMD).

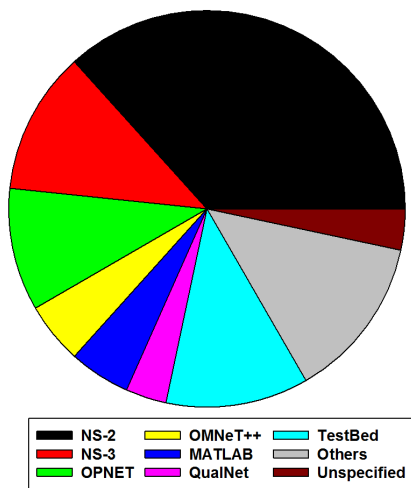


FIGURE 25. Simulators used in discussed routing protocols.

## B. VALIDATION STRATEGY

A realistic evaluation of FANET routing protocols requires the use of an important number of UAVs and maybe a certain number of base stations. Even if a number of research projects have enough budget to cover all necessary expenses, some flight restrictions are imposed by the law of certain countries for security purposes or in order to avoid specific areas reserved for other aircrafts [234]. For this reason, the majority of FANET research is highly dependent on software simulations for applications and protocols. Recently, some simulation tools always update their packages to support more realistic environments and provide accurate results. Some others release new versions to support the newly requested needs. As shown in Figure 25, different simulators are used to evaluate the performance of FANET routing protocols. NS-2 dominates other simulators in the domain of FANET communication since it is mastered by the majority of researchers and provides sufficient flexibility to simulate different experimental scenarios. Some other simulators have already been used to validate FANET protocols in the

literature, such as NS-3 and OPNET. However, there are a lot of personalized tools and extensions that have been developed, which provide a graphical interface and realistic behaviors of UAVs.

## VII. FUTURE CHALLENGE PERSPECTIVES

The recent advancement in UAVs technology paves the path for an exponential occupation of such devices in every sector of our life. Moreover, this technology could provide redoubtable assistance to existing services and create new applications never imagined before. The establishment of any applications or services involving UAVs is successful only when they are networking in an ad-hoc manner. However, this technology faces many challenging issues comprising especially technical issues, such as the frequent disconnections, the limited bandwidth, the higher packet latency, and the restricted energy capacity of UAVs. Also, the regulatory issues should be reviewed so that UAVs will be within everyone's reach and may benefit from them. Although, many researches have been carried out to overcome certain challenges, there are numerous unsolved issues, which should be investigated as future perspectives. Below, we discuss some of them along with their issues and proposed solutions for a promising exploration with the aim to create new research directions. Before we proceed, TABLE 16 highlights the different open research challenges along with the different crucial problems, the proposed solutions, and the recommended references in case when researchers want a deep investigation.

### A. P2P UAV COMMUNICATIONS

A fleet of UAVs requires cooperative synchronization and collision avoidance using peer-to-peer (P2P) communications. Since UAVs are able to act as data providers, they are appropriate for the P2P data and file sharing. Consequently, developing new P2P approaches and converge cast traffic can be a challenging topic for FANET communications.

### B. REGULATIONS FOR CIVILIAN UAVs

Despite their important usefulness in different contexts in our daily life, UAVs and their development do not fit with most of countries' current airspace regulations constituting their biggest obstacle. By defining accepted restrictions, the use of UAVs should be both monitored and improved in order to be optimally exploited to assist people on the ground. Consequently, there is a serious need to urgently deploy distinctive regulations to adopt UAV in both commercial purposes and research on improving the privacy and security of people.

### C. ENERGY SUPPLY EFFICIENCY

As it is already known, UAVs have a restricted energy capacity with batteries. Permanent developments are being made in battery technologies in order to allow UAVs to make long flight time by mainly exploiting green energy sources (e.g., solar energy). Nevertheless, this energy harvesting does



**TABLE 16. Open Research issues for FANET communications.**

	Problem(s)	Proposed solution(s)	Recommended reference(s)
P2P UAV communications	No specific routing mechanism is proposed yet.	Modified data-centric routing protocol can be used in this matter.	Refs. [235], [236]
Regulations for civilian UAVs	Restriction for civil users.	Proper rules and regulation can be imposed by the different government organizations.	Ref. [30]
Energy supply efficiency	<ul style="list-style-type: none"> <li>Limited energy capacity of UAVs.</li> <li>Low flight time.</li> <li>High packet loss.</li> </ul>	Propose energy-efficient routing protocols, study novel technologies of energy delivering (e.g., beamforming), and investigate the deployment of recharge station.	Ref. [237], [238]
UAV placement	<ul style="list-style-type: none"> <li>Integrate all the required sensor in a single unit.</li> <li>Energy constraints</li> </ul>	Energy efficiency model can be developed for FANET.	Refs. [4], [239]
Coordination of UAVs with Manned aircraft	Collision between UAVs and Manned aircraft.	Separate aircraft channel should be proposed for UAVs system.	Ref. [240]
Vulnerabilities against attacks	Mainly focused on gaining control or important information gathering.	Different layer security model can be proposed in the near future so that when FANET transmission gets popular vulnerability is not on the barrier side.	Refs. [241], [242]
Cryptography and security key generation	Existing conventional cryptography models might not suitable for FANET environment. Also, the generation and the transmission of security codes are also another open research area in terms of FANET.	A modified cloud security system can be specially developed in the data link layer of transmission protocol. Moreover, lightweight cryptography is an actively developing field.	Ref. [243]
Wireless transmission technology	Several wireless devices share the same transmission bands with FANETS becoming more overloaded.	Dedicated communication bands need to be specified by IEEE for FANET communication.	Refs. [56], [244]
Network fault tolerance system	No dedicated fault-tolerant system has been designed for FANET.	There is a vast opportunity in this concept for future research. Conventional ad hoc network fault tolerance system can be applied initially in FANET and the results can be observed for further modification.	Ref. [245]
Building trusted network model	FANET topology changes more rapidly than any other ad hoc network topologies. As a result, calculating the trust issue for both direct and indirect communication is much more difficult.	There are already some research works in this field. On research based on fuzzy logic is discussed the perspective on trusted networks. More research work can be conducted as this field is an open research issue so far.	Refs. [246], [247]
Radio propagation models	Propagation models are required to take into account the different dynamic mobility parameters of UAVs and their modeling into a defined radio channel.	Mathematical models have to be applied to define the most appropriate propagation models.	Refs. [248], [249]
Wireless Sensor Networks aspect	Very little work has been done regarding wireless sensor networks in terms of UAVs communication.	Conventional wireless sensors will not work in an aerial network. As a result, a new unit can be proposed so that the sensor range can be covered in FANET topology. Again, new sensor discovering can be a lucrative area for future researches.	Ref. [250]
Building distributed networks for UAVs	Very little work has been done in this research area. Also, the testing tools are yet to be applied.	A new distributed platform can be a dedicated design for UAVs communication.	Ref. [251]
UAVs control through cloud-based system	The security is one of the main concerns for cloud-based communication. Security key generation and exchange are also very challenging issues.	Before applying in the real world scenario, some test-bed experiment can be done to analyze the behavioral pattern of UAVs while using cloud-based monitoring system.	Refs. [252], [253]
Cross-layer routing	Very little works have been proposed in the area of cross-layer FANET routing. Moreover, there is no cross-layer proposals considering all layers during the routing process.	Developing new cross-layer routing protocols considering the unique characteristics of FANETS and their different issues.	Refs. [31], [254]
Routing challenges	Frequent link disconnections due to the high mobility and the reduced number of UAVs in the sky. Moreover, the negligence of many crucial UAVs' characteristics.	Designing new routing protocols handling these issues in an efficient way.	Ref. [28]

not satisfy both the long distances transited by UAVs and the amount of data traffic to make. The first alternative is that UAV has to exploit cooperation with other UAVs to overcome its individual energy restriction. The second alternative is to study the optimal placement of the recharge stations.

#### D. UAV PLACEMENT

In the different proposed strategies of UAV placement, two different problems have been distinguished. First, since it

has a restricted payload, a single UAV cannot be equipped with all kinds of devices (e.g., camera, sensors, aerial base station, etc.) at once. This requires to deploy multiple UAVs where each one is equipped with a single device and it has to be positioned at the right place to achieve a given mission successfully. Second, the energy consumption in UAVs is of major concerns. Indeed, the residual energy of UAVs is not only able to support the communication of information with surrounding entities, but also supplies their both different

integrated components and propulsion energy. In the majority of cases, each task assigned to a UAV can be different from another UAV's task, thus differentiating the energy consumption. Consequently, it is important to extend the UAV functioning lifetime, according to the nature of the task. Regarding this, optimizing UAV placement to define both the optimal required number of UAVs and their locations are still an open challenge and a hot topic to explore.

#### **E. COORDINATION OF UAVS WITH MANNED AIRCRAFT**

The cooperation of autonomous UAVs with other manned aircraft is crucial in different sides, such as improving the connectivity of a given zone, ensuring the detection and destruction of suspect aircraft, and avoiding collision between each other. To do so, this heterogeneous cooperation should be in an ad hoc networked manner. Therefore, several open challenge issues have been distinguished and ready to be investigated, such as monitoring missions involving the two kinds of flying units, a common band to communicate, and extending the network coverage.

#### **F. VULNERABILITIES AGAINST ATTACKS**

Accurate knowledge of network vulnerabilities can determine how good it is protected. A network such FANET is not free from malicious UAVs making its security a very critical issue. Moreover, UAVs are conceived based on embedded autopilots to fly, and thus can be vulnerable to possible cyber attacks. Also, since the network layer is considered as a central interest to support the majority of applications, it is crucial to take into account this critical issue. Consequently, before proposing any security features, it is very important to perform a deep study to enumerate the different vulnerabilities of FANETs against different kind of attacks.

#### **G. CRYPTOGRAPHY AND SECURITY KEY GENERATION**

A lot of critical information is exchanged between UAVs and intercepting them by a malicious entity has a disastrous consequence on this kind of network. In this case, cryptographic approaches are deployed to alter readable information into meaningless one, thus ensuring the confidentiality and integrity of such information. However, cryptographic protection is complex by the fact that UAVs have a limited energy capacity and they cannot efficiently make cryptographic calculations. Consequently, Generating different security codes has been always a challenging issue.

#### **H. WIRELESS TRANSMISSION TECHNOLOGY**

To communicate, UAVs have firstly used existing wireless communication bands (*e.g.*, UHF and L-Band) that are already used by different telecommunication systems, such as GSM networks and satellite communications. Recently, WiFi nodes are embedded in UAVs to perform simultaneous communications in both the 2.4 GHz and the 5 GHz bands supporting both U2U and U2G communications, respectively. However, there is a serious need to standardize these communications bands in order to minimize the frequency

congestion problem, making this a very important open challenge issue.

#### **I. NETWORK FAULT TOLERANCE SYSTEM**

Adopting a fault-tolerant system in a FANET is crucial to keep the network running despite the failure of some of its components. There are two different ways to make the network more tolerant to faults: (i) hardware side by adding extra redundant UAVs and (ii) software side by duplicating messages, processes, or codes, according to the situation. Consequently, a fault-tolerant system is considered as a vital issue and needs a deep investigation.

#### **J. BUILDING TRUSTED NETWORK MODEL**

In a FANET, UAVs frequently exchange data packets between each other, and thus they are very dependent on neighbor UAVs to accomplish a given mission. This is why the communicating UAV has to ensure that only packets from authenticated UAVs (*i.e.*, trusted UAVs) are allowed to be intercepted. Consequently, building a trusted network model is useful to reduce the vulnerability against non-trusted UAVs from interacting with trusted UAVs, thus making this a very important challenge to study.

#### **K. RADIO PROPAGATION MODELS**

A propagation model is adopted between any communications between a pair of source and destination UAVs. This model has to take into consideration several effects, such as speed, altitude, and velocity angles, which define the characteristics of the radio channel. These latter can be mathematically modeled in order to a propagation model that provides a rapid spread of UAVs. This is a hot and timely topic and it is currently in a theoretical stage, thus requiring a lot of research and study to obtain the appropriate propagation model for this kind of communication systems.

#### **L. WIRELESS SENSOR NETWORKS ASPECT**

Just a few works have been carried out regarding WSN involving UAVs communication. Indeed, due to their high and controlled mobility, UAVs can be exploited to act as a mobile data collector for the sensors located on the ground while considering their energy restriction capacity. Consequently, WSNs are a very hot topic comprising several issues to investigate, such as the mobility and altitude of UAVs, the data collection of data from sensors, and wireless radio channel to be adopted.

#### **M. BUILDING DISTRIBUTED NETWORKS FOR UAVs**

A distributed network comprises a large number of UAVs coordinating to perform a common mission without relying on a centralized infrastructure. Such a network requires that tasks of each UAV need to be cooperatively planned beforehand in order to efficiently achieve the whole mission. However, the architecture of a classical FANET always involves a ground base station to both manage the exchange information and intercept crucial information about

the mission. Consequently, a distributed subsystem needs to be built in order to allow UAVs to work cooperatively only by exchanging information between each other.

#### N. UAVs CONTROL THROUGH CLOUD-BASED SYSTEM

Due to the limited energy resources and calculation capacity of UAVs, an effective solution has to be deployed to exploit the existing resources of all UAVs. To address these issues, a recent investigation proposed to integrate cloud computing paradigm with FANETs. Nowadays cloud computing is a very popular platform and can be considered as an effective solution to extend resources capacity of such networks. However, since the resources can be shared among UAVs, the security is one of the main concerns of cloud-based systems. This kind of systems has to adopt security mechanisms, which need realistic experiments to be validated. Moreover, control through cloud-based monitoring and control system are among the hot topics that are investigated only ostensibly and they are yet to be applied.

#### O. CROSS-LAYER ROUTING

Most of the discussed routing protocols in this paper are focused only on addressing issues with an individual protocol layer (*i.e.*, Network layer), which is responsible for maintaining connectivity between UAVs. However, the other layers, such as the physical and data link layers are more involved in power control of devices and avoiding collisions of packets, respectively. Cross-layer approaches can provide more flexibility in which all layers exchange knowledge by creating new interfaces between each other about a certain situation of the network and then they react accordingly. The area of routing cross-layer protocols in FANETs is not widely investigated and it is still an open issue.

#### P. ROUTING CHALLENGES

Both the high mobility and the low density of UAVs are the major issues towards designing an efficient routing strategy ensuring a robust data exchange between UAVs. The severity of these issues is increased when UAVs move in a 3D space (*i.e.*, different altitudes). Different techniques have been proposed across the literature based on a single situation encountered in the network. However, they cannot deal with all issues that can be met with a network as FANET. Consequently, there is a serious need to propose new protocols that could deploy the appropriate technique in a given kind of situation.

### VIII. CONCLUSION

In FANETs, routing is considered as one of the main components to ensure a right functionality and efficient cooperative network operations. During the last decade, some sixty protocols have been proposed in the literature. Each one has its own characteristics, features, drawbacks, and competitive advantages. To differentiate them and put things in the clear, this comprehensive survey surveyed the most important features that have a strong relationship with FANET routing. At a first step, we have identified the majority of the survey

works and compared them qualitatively based on outstanding points in order to allow showing the novelties of our survey. Then, this survey describes in an original way the architecture of FANETs by describing the different adopted organizations, the existing kind of communications, and their characteristics. Also, a brief comparative analysis between MANET sub-classes in terms of several crucial features has been presented so that the readers have a clear idea about the most challenging kind of networks. Finally, since the mobility models play a key role in defining the effectiveness of a given routing protocol, we reviewed the existing FANET mobility models that are classified according to a taxonomy, and then they are compared with each other based on different metrics.

As a second step, the most adopted techniques by the FANET routing protocols are described. After that, a global taxonomy of these FANET routing protocols is provided, in which the protocols are categorized into eight main categories and ten sub categories. Each category is described separately along with explanatory figures of its routing protocols that are then compared with each other based on different characteristics. At the end of this study, a global comparative study between all categories is presented based on several parameters, such as the adopted routing techniques, the required requirements and features, and the methods of validation. This study allows us to select the most adequate routing strategy that is the most appropriate to a given situation. A brief study that highlights the most used simulation tools to validate the functioning of the proposed routing protocols is presented.

As a final step, we have identified the less investigated open research challenges and requirements for FANET routing protocols. Moreover, we have provided possible solutions and some recommended references for scientists who would like to explore more deeply in this research area. As a final conclusion about this work, we can say that FANET routing protocols must deal with the fragmentation of network and the highly dynamic topology of the network. As future perspectives, which we are currently studying is to specialize towards UAV-assisted concept which has been less investigated and recently has attracted the interest of an important number of sciences. Moreover, we plan to conceive an efficient routing protocol that can be adapted to every situation while considering the different studied constraints.

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