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Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey

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ABSTRACT Unmanned aerial vehicles (UAVs) have gained popularity for diverse applications and services in both the military and civilian domains. For cooperation and collaboration among UAVs, they can be wirelessly interconnected in an ad hoc manner, resulting in a UAV network. UAV networks have unique features and characteristics that are different from mobile ad hoc networks and vehicular ad hoc networks. The dynamic behavior of rapid mobility and topology changes in UAV networks makes the design of a routing protocol quite challenging. In this paper, we review the routing protocols for UAV networks, in which the topology-based, position-based, hierarchical, deterministic, stochastic, and social-network-based routing protocols are extensively surveyed. The routing protocols are then compared qualitatively in terms of their major features, characteristics, and performance. Open issues and research challenges are also discussed in the perspective of design and implementation.

INDEX TERMS Unmanned aerial vehicle network, flying ad hoc network, drone ad hoc network, routing protocol, rapid mobility, dynamic topology, scalability.

I. INTRODUCTION

The rapid deployment of low-cost Wi-Fi radio interfaces, global positioning system (GPS), sensors, and embedded microcomputers has enabled unmanned aerial vehicles (UAVs) to be extensively used for various applications in the military and civilian domains. Examples of military applications are public protection and disaster relief operations [1], surveillance and reconnaissance [2], border supervising [3], autonomous tracking [4], managing wildfire [5], homeland security [6], wind estimation [7], remote sensing [8], traffic monitoring [9], and relays for ad hoc networks [10]. In addition to military and public domains, there are also numerous commercial applications for UAVs, such as film making [11], farming [12], Internet delivery [13], goods transportation [14], and architecture surveillance [15]. Nokia deployed a 2 kg weight ultra-mini 4G mobile base station, which was successfully mounted on a commercial quadcopter to provide coverage over a remote area in Scotland [16]. Similarly, Amazon designed a small drone named Amazon Prime Air [17] to deliver customer parcels safely within 30 minutes.

Deploying a large number of drones introduces challenges, such as ensuring collision-free and seamless operation of the drones. UAVs can be categorized into four types based on their cruise durations, and action radius: high-range UAVs operating at high altitude, with long endurance; medium-range UAVs with action radii between 700 and 1000 km; low-cost, and small short-range UAVs with action radii less than 350 km, and flight spans less than 3 km; and mini drones with limited cruising speeds of 10 to 30 km/h, and cruising durations of less than 1 h.

For proper cooperation and collaboration between multiple UAVs, inter-UAV wireless communication is necessary for forming a UAV network, or a flying ad hoc network (FANET). The UAV is also called drone, and thus the three terminologies, UAV network, FANET, and drone ad hoc network, are interchangeably used. There are two types of UAV networks, as shown in Fig. 1. In a single-UAV network, the UAV is linked to a ground base station, or to a satellite. In a multi-UAV network, multiple UAV devices are linked to each other in addition to the ground base station, or satellite. The UAVs in a multi-UAV network can be configured dynamically in different topologies from time to time. The UAV to UAV connection and the UA to ground base station connection are called U2U link and U2G link, respectively.

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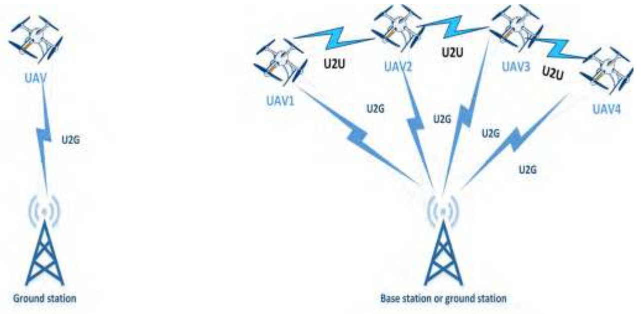

(a) Single-UAV network (b) Multi-UAV network

FIGURE 1. **Single- and multi-UAV networks.**

TABLE 1. **Summary of existing survey articles on UAV networks.**

Article	Major features and characteristics
Ref. [28]	Introduces a comprehensive survey on UAVs; different networks that can be formed with, or by UAVs; UAV-based architecture for UAV-based IoT services; and the adoption of different communication technologies among UAVs, and the ground infrastructure.
Ref. [29]	Surveys the existing UAV frameworks and cooperative network formation; additionally, a comparative study of various software solutions, simulators, test beds available for implementation, and testing of UAV-oriented networks are included.
Ref. [30]	Surveys research in the areas of topology-based routing, and introduces seamless handover, and energy efficiency.
Ref. [31]	Introduces the networking architectures of UAVs, discusses various communication protocols and technologies that can be used in different links, and the layers in a UAV-based networking architecture.
Ref. [32]	Studies differences between FANETs, MANETs, and VANETs. Along with the existing FANET protocols, existing FANET testbeds, and simulators are also presented.
Ref. [33]	Provides the characteristics and requirements of UAV networks for envisioned civilian applications from a networking viewpoint, and observes that IEEE 802.11 technologies are commonly used in commercial small-scale UAVs.
Ref. [34]	Surveys UAV network models, and the challenges of relay nodes in UAV networks.
Ref. [35]	Introduces a comprehensive survey of position-based routing protocols for FANETs with their various categories.
Ref. [36]	Presents a comprehensive survey of cluster-based routing protocols for UAV networks with various clustering approaches.
Ref. [37]	A comprehensive comparative analysis of geographic routing protocols for three-dimensional network scenarios.
Ref. [38]	Presents a comprehensive survey on single-hop routing, proactive, reactive, hybrid, and position-based routing.

A routing protocol is essential for the transmission of packets between UAV nodes; however, there are challenges associated with developing it. One of them is the highly dynamic topology of UAV networks, which means that UAV links may be frequently disconnected. Another challenge is the range restriction between the UAVs and the base station. Therefore, high mobility, dynamic topology, and uneven UAV distributions make the development of a routing protocol ensuring reliable communication difficult in UAV networks [18], [19].

In some situations, UAV networks may be noticed as a special form of mobile ad hoc networks (MANETs), and vehicular ad hoc networks (VANETs). Recently, significant research work has been done by applying existing ground networks, such as VANETs, to UAV networks [20], [21]. However, the rapid mobility and highly dynamic topology in UAV networks make the adaptation challenge, thus limiting network performance and dependability. Several approaches and contributions have been proposed, particularly those based on geographical position during the last few years. These routing protocols have been designed based on frequent disconnections between the UAV nodes owing to their high mobility. In addition, the routing protocols [22], [23] designed for MANETs can be improved by including the unique functions and characteristics of UAV networks.

Different mobility in a multi-UAV environment requires highly accurate localization with short update intervals. GPS provides node position information at one-second intervals, which may not be satisfactory for UAV routing protocols. In such case, an inertial measurement unit was considered, which can be calibrated by the GPS signal to provide the position of the UAV at a quicker rate [24], [25]. Some researchers proposed differential GPS (DGPS), or assisted GPS by using ground-based reference methods for range corrections with the accuracy of about 10 m [26], [27].

In the last few years, comprehensive surveys on UAV routing protocols have been reported [28]–[38] as summarized in Table 1-that provide information on the general issues in UAV networks, such as in applications, communication protocols, and routing techniques. Of them, only few survey articles [30], [35] provide details on UAV routing techniques, *e. g.*, [30] reviews a few well-known topology-based routing protocols; [35] surveys a few position-based routing protocols; *i. e.*, they do not provide the details on all routing protocols, such as topology-based, and cluster-based routing protocols.

The objective of this study is to survey the routing protocols applicable to UAV networks, where position-based, topology-based, cluster-based, deterministic, stochastic, and social-network-based routing protocols are extensively reviewed. In our work, we introduce a comprehensive survey of 21 topology-based routing protocols, 22 position-based routing protocols, 5 cluster-based routing protocols, 6 different data forwarding-based routing protocols, and 6 field experiments of routing protocols in UAV networks and FANETs with their various categories. After discussing network architecture, various routing techniques, and taxonomy of routing protocols in UAV networks, we compare the routing protocols qualitatively in terms of their major features, characteristics, and performance. Then, we address important open issues and research challenges in designing routing protocols for UAV networks.

To the best of our knowledge, this is the first article that studies all categories of routing protocols reported in the literature. In the recent time, some survey papers reviewed routing protocols in UAV networks as summarized in Table 1. However, none of them has focused on all categories of routing protocols in UAV networks. Most of the survey papers in the literature focus neither on position-based routing nor on topology-based routing. In our work, we deeply describe and compare all categories of routing protocols including position-based, topology-based, cluster-based, deterministic, stochastic, and social-network-based routing in UAV networks. Each category of routing protocols are also classified into different sub-categories. In addition, we include recent routing protocols from the literature.

The rest of this paper is organized as follows. In the following section, the design considerations for UAV networks are summarized. In Section III, UAV network architectures and communication issues are addressed. In Section IV, the routing protocols for UAV networks are presented, in which topology-based, position-based, hierarchical, deterministic, stochastic, and social-network-based routing protocols are extensively surveyed. In Section V, the different routing protocols are qualitatively compared in terms of their characteristics and performance. In Section VI, important open issues and research challenges are discussed. Finally, the paper is concluded in Section 7.

II. DESIGN CONSIDERATIONS FOR UAV NETWORKS

UAV networks have several crucial points of design owing to their unique characteristics. In this section, we briefly discuss the architecture, characteristics, and mobility models of UAV networks. Owing to rapid changes, and activities during the network operation, UAV networks require high scalability, adaptability, and robust communication protocols [39].

A. TOPOLOGY

Peer-to-peer connections are formed between the UAVs to maintain coordination and collaboration; either single-cluster or multi-cluster formations can be used to complete this task [40]. For homogenous and small-scale missions, a single cluster is the best choice. When certain UAVs must perform multiple missions, the need for multi-cluster networks arises. In this design, the cluster head of each cluster is responsible for downlink communication and communication between other cluster heads.

B. MOBILITY

A mobility model is necessary for efficient communication between UAVs; it captures their trails and speed deviations. In UAV networks, mobility models are application-dependent. In the case of some multi-UAV systems, global path plans are preferred for the UAVs. In this case, the movement of the UAVs is predefined, and the mobility model is regular. However, multi-UAV systems also work autonomously, where the path is not predefined. Mobility models also depend on the type of UAV considered. UAVs are categorized as large UAVs, small UAVs, and mini-UAVs [41]. For the motion of UAVs performing autonomous military operations in groups without a centralized control as a point of reference, group mobility model (RPGMM) can be the best choice. An example of RPGMM is Manhattan grid mobility model, which can be used to emulate a map-based approach while considering the geographic restrictions of the UAVs [42]. For patrolling applications, where UAVs can adopt flexible trajectories, other models, such as random waypoint mobility model can be used [43]. In yet another model, the Gauss–Markov mobility model, the movement of UAVs depends on previous speed and directions that assist UAVs in relaying networks [42].

Node mobility is a significant issue in UAV networks, as well as other ad hoc networks. Compared to VANET nodes, MANET nodes are relatively slow. The mobility of FANET nodes are higher than that of both VANET and MANET [24]. All UAV nodes are highly mobile, with speeds ranging from 30 to 460 km/h [44]. This results in fluctuations in the wireless link, and, as such, the efficiency of routing techniques varies on the speed of the UAVs. A routing layer ensures end-to-end delivery, and medium access control (MAC) ensures the quality of service (QoS) for one-hop transmission [45].

C. LATENCY

Disaster monitoring, and search and destroy operations require minimal latency, as the information needs to be transmitted at very high rates. It is almost impossible to have a network without delay; however, latency in a network can be minimized and controlled within certain limits. The concept of priority schemes may also be used in UAV networks to control and minimize latency [46]. In addition, priority-based routing protocols can be used to achieve QoS for various message types. Coordination among UAVs, performing efficient collision control, and congestion control protocols also play vital roles [47]. Therefore, choosing the best suitable routing protocol essential in controlling the latency and improving the QoS of UAV networks.

In [48], authors aim at solving the end-to-end delay-constrained routing problem in a local way for FANETs. Due to the high mobility, getting global information for each node is a difficult task. To resolve this issue, the authors in [48] designed an adaptive delay-constrained routing with the aid of a stochastic model, which allows senders to deliver packets with only local information.

D. FREQUENT LINK DISCONNECTION

Due to the dynamic rapid mobility of UAVs, the network density varies, which may occur the frequent disconnection of the network. The link disconnection is higher in a sparse network. In a high-density network, UAVs are easily connected. Conversely, in a low-density network, links are frequently disconnected; therefore, the high rates of broken communication and long delay occur. To ensure the communication quality, a robust routing protocol is needed to identify the frequent disconnection and to provide an alternative link easily and rapidly.

E. PREDICTION

For making communication between UAVs, the information of UAV position and movement is required. In high-speed

UAV networks, it is very difficult to predict the position of UAVs due to the dynamic mobility of UAVs. The position of UAVs is predicted on the basis of UAV speed, moving direction, and predetermined mobility model.

F. FLIGHT FORMATION

In [49], a new formation for flight control protocol in multi-UAV systems is introduced, which is based on the diverse and asymmetric delays and dynamically changing topologies. The authors in [49] proposed a consensus-based distributed formation control protocol to address the stability problem in the multi-UAV formation, which needs only the local neighbor-to-neighbor information between UAVs. The simulation result indicates that if the communication topology is jointly connected and the non-uniform delays satisfy the design requirements, then the multi-UAV system can shape the desired formation and maintain the expected velocity, heading angle, and expected flight path angle. However, the size and collision avoidance of UAVs are not considered in [49].

In [50], authors presented multi-UAV cooperative formation at high-speed flight. During the high-speed flight, when a single UAV needs to exit from the flight formation or needs to join in the flight formation quickly, design controller faces colossal challenge. Both the inner loop controller and outer-loop controller are based on nonlinear dynamic inversion control.

G. COLLISION AVOIDANCE

In [51], authors introduced a Kalman filter based obstacle's position estimation and prediction algorithm. The proposed algorithm calculates reference trajectory based on the information of other UAV's position, and the predictive controller tracks the reference point.

H. COMBAT WITH EXTERNAL DISTURBANCES

A fully autonomous multi-UAV network needs robust inter-UAV communication even in case of node or link failure. Multi-UAV networks require self-organizing capability, flexible and automated control, and delay-tolerant capacity. To address these issues, UAV networks would require changes in the MAC and routing layers. For self-configuration and reorganization, ad hoc networks are considered as an appropriate solution for UAV networks. Fault-tolerance feature enables UAV networks to become resilient to the failure of one or more nodes. Even when a node fails or a new node appears, neighbor discovery process makes UAVs find available neighbors dynamically. The level of disruption relies on several parameters such as how mobile the UAVs are, the power transmitted, inter-UAV distances, and extraneous noise. In the applications where UAVs provide communication coverage to an area, the UAVs are hovering and, therefore, the probability of disruptions would be low. Conversely, the application based on fast UAVs have a higher probability of disruptions. Poor link quality and unavailable path between sender and receiver result in additional delay.

In [52], authors presented that the mutual collision avoidance problem of UAVs should be taken into design consideration for the mission-critical applications such as covert penetration and active combat against enemy. In addition, the communication constraint problem in such networks is also addressed. The authors in [52] used particle swarm optimization technique to solve the cost function of multi-UAV formation.

I. SCALABILITY

In both single-UAV and multi-UAV systems, collaboration between UAVs can increase the performance of the system. For most applications, performance enhancement is proportional to the number of UAVs, *e. g.*, the higher the number of UAVs, the faster a search and rescue operation may be completed [53]. Therefore, in the design and development of a UAV routing protocol, we should consider whether a good number of UAVs could perform together at a time without performance degradation.

III. UAV NETWORK ARCHITECTURES AND COMMUNICATION

In this section, the fundamental architectures of UAV networks are introduced, and communication issues addressed.

A. UAV NETWORK ARCHITECTURE

Nowadays, most public and civilian applications can be performed using multi-UAV networks. Most of these multi-UAV networks are small, and the UAVs work in coordination. Multi-UAV networks are comprised of several components, such as UAVs, and ground control systems; hence, the networks may have several layers, such as UAV-to-UAV communications, and UAV-to-ground communications. The key features of multi-UAV networks are reliability and survivability through the redundancy. Failure of a single UAV causes the network to reorganize and maintain communication via other nodes.

UAV networks can be categorized based on their applications, which requires certain specifications, such as the degree of node mobility, network architecture, routing, and control. Depending on the scenario, a UAV may be used to form different networks. Latency, scalability, and adaptability are fundamental design issues in implementing UAV networks. Moreover, for mission-critical network designs, packet delay is a significant issue [54], [55]. Furthermore, for large area coverage, the number of nodes is a key issue [44]. Fig. 2 shows the taxonomy of UAV networks.

B. COMMUNICATION IN UAV NETWORKS

Although MANET, VANET, and FANET have many characteristics that are different from each other, they have several common design considerations. FANET is special subnet of MANET and VANET, for which IEEE 802.11 MAC protocols, which are widely used in MANET, have been used with an omnidirectional antenna [56], [57]. Wajija Zafar *et al*. proposed the use of another protocol, called IEEE 802.14.4 [36]

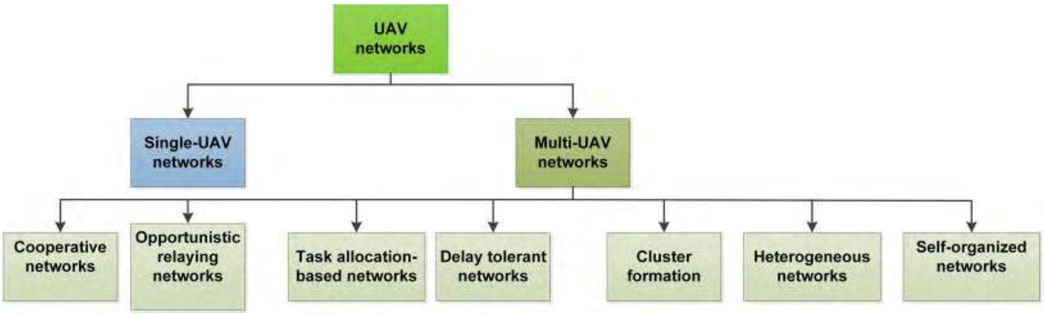

FIGURE 2. Taxonomy of UAV networks.

for MAC, which is low power, less complex, and has a lower data rate. Researchers have proposed IEEE 802.14.4 for UAV-to-UAV communications, where bandwidth requirements are less. They also proposed IEEE 802.11 for UAV-to-ground communications because it can handle more bandwidth, with high data rates, and long-range coverage. During real-time communication among UAVs, the MAC layer should address a few challenges, such as packet delays, optimal channel utilization, high mobility, and variable link quality. In UAV networks, the link quality fluctuates occurred due to varying distances between nodes, and high mobility.

1) AIR-TO-AIR WIRELESS COMMUNICATION

Between UAVs, and the UAVs and the ground base station, to avoid restrictions on the transmission range, UAVs can communicate with each other using only ad hoc network architecture. This wireless network is used to transmit data between nodes in various applications, and in multi-hop communications [56].

2) AIR-TO-GROUND WIRELESS COMMUNICATION

In UAV networks, not all UAVs can communicate with the ground station, or satellites [57]; rather, only a select few do to improve connectivity, in addition to their delivery of other services.

IV. DESIGN TECHNIQUES FOR ROUTING IN UAV NETWORKS

Because UAV networks each have unique characteristics, they have their own routing mechanisms, yet, some common techniques can be utilized for data transmission. However, a suitable forwarding process must be adapted to the mobility model and the functional scenario in UAV networks [58]. To avoid packet loss, the selection of relays to forwarding data is important as well. Some design techniques for routing in UAV networks are discussed in this section.

A. DELIVERY SCHEME

Fig. 3 presents the different delivery schemes of unicast, broadcast, multicast, and geocast routing. Unicast routing is direct hop-to-hop communication between a sender and a receiver. The broadcast routing that floods messages over the network. Flooding-based strategy enhances the delivery probability, but requires high bandwidth and overhead. Broadcast-based scheme is suitable for scattered networks; when the network density increases, they become less efficient. Geocast routing and position-based routing have similar properties. A geocast-based protocol uses a multicast routing to deliver a message to all nodes situated in a specific geographical area. That is, it delivers the packet from the source node to all nearest nodes in the same geographic area.

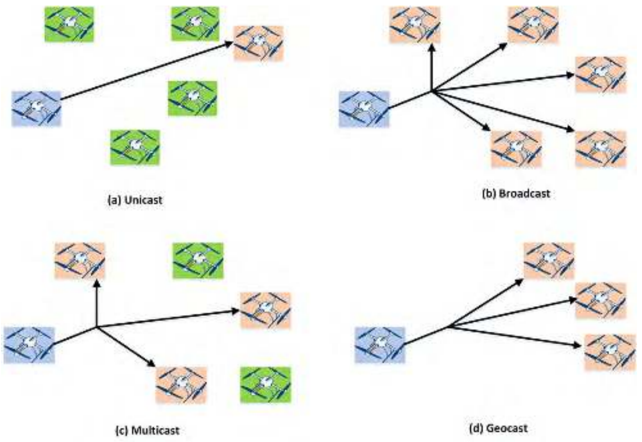

FIGURE 3. Different delivery schemes in routing.

The multicast routing maintains a network organization such as tree or mesh structure. Tree-based protocols maintain a multicast routing tree to transfer from a source to a group of destination nodes. The key drawback of tree-based approach is that the tree needs to be rebuilt when the topology is unstable. As a result, routing service is frequently disrupted. In a highly dynamic network, maintaining the topology is a main challenge.

B. COOPERATIVE ROUTING

Cooperative routing is a promising approach to increase the reliability of communications. In the cooperative routing, node helps each other with information transmission by exploiting the broadcasting scheme. Neighboring nodes are considered as a relay node in cooperative routing. The idea of cooperative routing is shown in Fig. 4. The cooperative

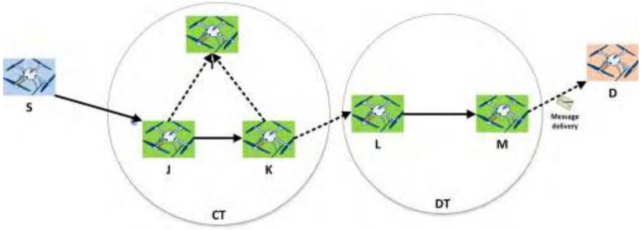

FIGURE 4. Cooperative routing process.

routing consists of cooperative transmission (CT) and direct transmission (DT) links.

C. PATH DISCOVERY

Discovery process is used when the geographical position of the target destination node is known by the source node. To reach the destination, a route request (RREQ) shown in Fig. 5 is sent to find the all-possible paths from source node to destination node. The best path is selected based on precise conditions when the target destination receives all possible paths. Then, the selected path is used for data transmission. Because of the simplicity of the path discovery process, it is used in existing routing protocols in UAV networks. Its benefit is that the packet will be transmitted via a low-cost path, which can reduce the transmission time, as well as losses.

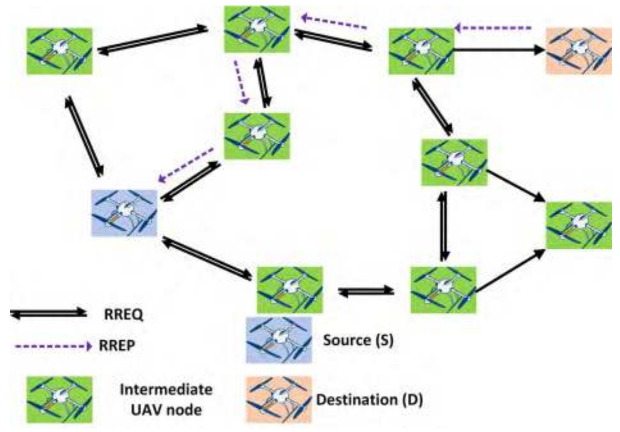

FIGURE 5. Path discovery process.

D. SINGLE PATH

The single-path method is used to transmit data between two communication nodes, where the routing path is calculated using simple routing tables. For a single path, a routing table is predefined, such that no alternative paths exist in the case of faults in the network. This is the limitation of this method, so path failures would result in packet losses. As shown in Fig. 6, single-path routing protocols learn routes and select a single best route to each destination.

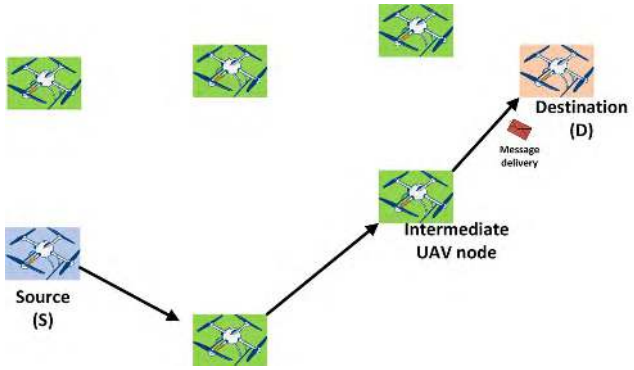

FIGURE 6. Single-path routing.

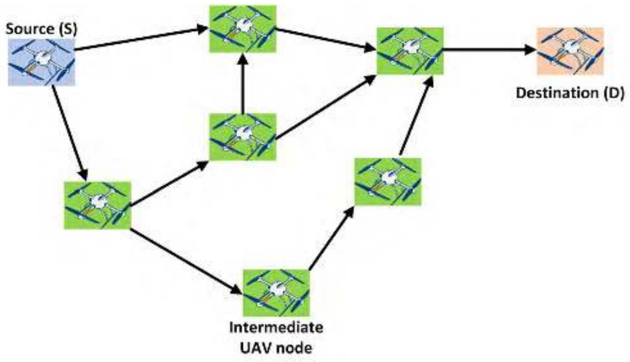

FIGURE 7. Multi-path routing.

E. MULTIPLE PATHS

As indicated by its name, multipath routing methods create several paths between the source and destination nodes as shown in Fig.7. Maintaining the routing table in multi-path routing is complex because of so many routing paths in the network. If there were any problem in the communication nodes, multi-path routing would have several choices to the destination. Another key reason to use the multipath routing is to defend against jamming attack or path failure in UAV networks. The multipath routing protocols also provide efficient and reliable data transmission as well as improve network resiliency in the presence of malicious jammers [118]. The major limitation of this method is its complexity, as maintaining a routing path is a big task, and risks the possibility of route loops in the network from the slightest error.

F. QUORUM-BASED ROUTING

Quorum-based routing is used to develop a location service. The location service and forwarding scheme are essential for position-based routing. The location service is needed to learn the current position of a specific node, in which four kinds of approaches can be used: some-for-some, some-for-all, all-for-some, and all-for-all. On the other hand, the forwarding scheme can be classified as restricted directional flooding, greedy forwarding, and hierarchical approaches.

G. GRID-BASED ROUITNG

In grid-based routing, the network area is divided into hierarchy of squares. The scheme is shown in Fig. 8.

Within the local first-order square, each node maintains a table of all other nodes. The routing table is periodically broadcast. All nodes in the first-order square have their own ID and the nearest nodes' ID. Position of each node is periodically broadcast in the first-order square area. The position of a node is considered as the center of the grid. After a node closely reaches the position, the position information is forwarded progressively. This guarantees that the position information reaches the correct node, where it is then stored. Grid-based location service needs that all nodes store the information for some other nodes; i.e., it can be classified as an all-for-some approach.

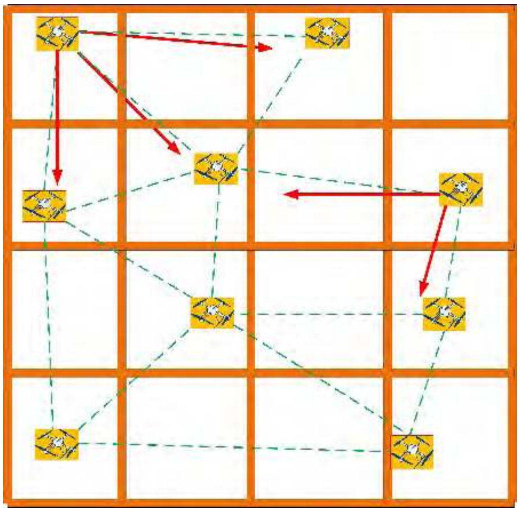

FIGURE 8. Grid-based routing.

H. STORE-CARRY AND FORWARD

Store-carry-and-forward routing technique is used when some fault in the network causes a disconnect from its next relay node, but forwarding data is necessary, and it is also not possible to transmit data to next hop, as the node is out of transmission range. In such a scenario, the current packet holder node carries the data until it meets another node or the destination node. Delay is the major disadvantage of this technique. Even though this technique may not work efficiently for FANET environment due to rapid topology changes, it is effectively used in FANETs in case the UAV nodes are sparsely distributed. As shown in Fig. 9, when the network suffers from intermittent connectivity, the forwarding node carries data packets until it meets with another node or reaches to the destination. In delay-tolerant networks, store-carry-and-forward routing technique can be exploited with ferrying UAVs. The store-carry-and-forward routing technique ensures high throughput in delay-tolerant routing in UAV networks.

I. GREEDY FORWARDING

When UAVs are densely deployed in a network, greedy forwarding may be required to communicate between two nodes. The main principle of this method is to minimize the number of hops in the transmission path. Its mechanism is to choose a relay node that is geographically nearest to the destination node, as shown in Fig. 10.

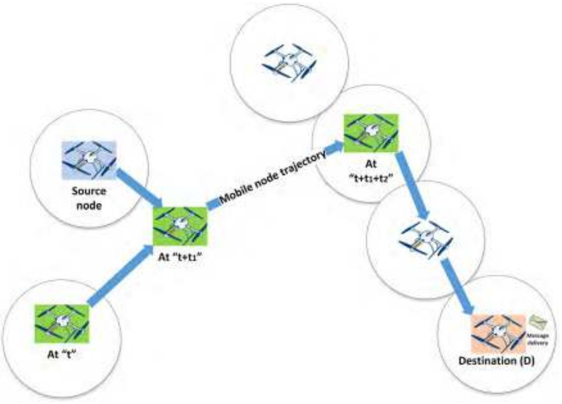

FIGURE 9. Store-carry-and-forward technique.

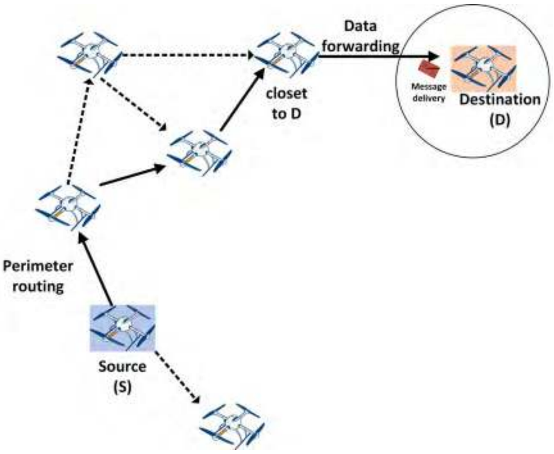

FIGURE 10. Greedy forwarding technique.

Greedy forwarding is a simple progress-based forwarding strategy. A node forwards the packet to the neighbor node that minimizes the distance to the destination node. If there is no neighbor node closer to the destination node, the algorithm fails and the node keeping the packet is called local minimum. In the greedy algorithm, distance between the current node and destination node can be compared against the distance between current nodes and neighbor nodes. It also used to select the forward nodes and the backward nodes.

The limitation of this method is its associated local optimum problem, owing to which it may not find the best relay node to reach its destination and huge overhead is another drawback.

J. PREDICTION

Several prediction methods are used in UAV networks. The most common prediction method is based on the direction, geographic location, and speed of the UAVs, which the source node uses to transmit data to the next node. These parameters usually provide reasonably good approximations about the next relay node in communication networks. Fig. 11 shows how predicting geographical location is used to find the next relay node. In some cases, the store-carry-and-forward method is used to avoid packet loss in the communication network. In addition, path discovery is also used to find active paths between communication nodes.

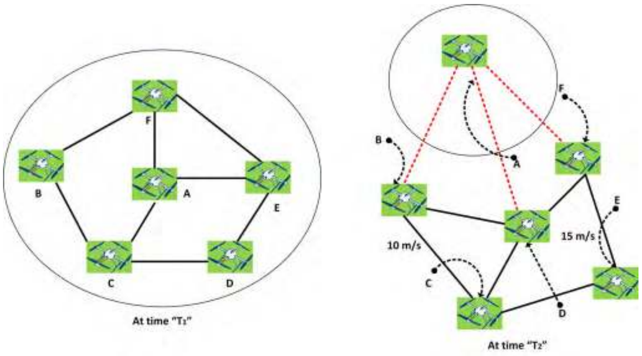

FIGURE 11. Prediction technique.

V. ROUTING PROTOCOLS FOR UAV NETWORKS

Several routing protocols have been proposed for UAV networks [23], [59]–[129]. Initially, MANET and VANET routing protocols were chosen for testbeds in UAV networks. Owing to the unique characteristics of UAVs, such as rapid topology changes and high mobility, however, the routing protocols designed for MANETs and VANETs were realized not to be suitable for UAV networks. Therefore, specific routing protocols for UAV networks have been proposed recently.

UAV routing protocols are classified into two different sections: Network architecture based routing protocols and based on data forwarding. Network architecture based routing are classified into three different subsections such as topology-based, position-based and hierarchical routing protocol. Topology-based routing contains three types of routing such as mesh-based, tree-based, and hybrid. Tree-based routing can be further classified into source rooted and core-rooted based routing. Source-rooted tree routing is multicast routing protocol, where the source node is the root of multicast trees and maintains the tree construction and distribution. In core-rooted tree routings, cores are nodes with special functions likes multicast data distribution and membership management.

In mesh-based routing, packets are distributed among the all interconnected nodes in the mesh structure. Mesh building and route discovery process can be done in two ways such as broadcasting method are used to discovering routes and core point is used for mesh building. Performance of mesh routing is better than tree-based routing in high mobility network, and mesh-based routing provides alternate paths to forward data packets from the source to destination. To maintain and manage the routing topology mesh-based routing needs control packets, which makes routing overhead and resulting in power inefficiency. In source-based routing, intermediate nodes need not maintain up-to-date routing information to forward the packet. The major limitation of source routing is overhead. In source routing, routing table is long for a large network and for every packet needs to mention the entire route in the header file, which is the cause of waste of network bandwidth. In hop-by-hop routing, route to the destination is distributed in the next-hop. In hop-by-hop routing, when node receives a packet to the destination, it forwards the packet to the nearest next hop corresponding to the destination node. Hybrid routing protocols are combines of both tree and mesh-based routing. Multiple routing paths are the major advantages of hybrid routing.

In this section, we review the routing protocols applicable for UAV networks, in which topology-based, position-based, hierarchical, deterministic, stochastic, and social network-based routing protocols are extensively surveyed. Fig. 12 shows the taxonomy of routing protocols for UAV networks.

A. TOPOLOGY-BASED ROUTING

Topology-based routing protocols use the existing node information to transfer packets within the network. To define the node, topology-based routing protocols exploit the IP addresses in the network. Due to high mobility and frequent topology changes, designing a routing protocol is a challenging task in UAV networks [59].

The routing protocols are divided into the following four categories:

i. Static routing protocols
ii. Proactive routing protocols
iii. Reactive routing protocols
iv. Hybrid routing protocols

1) STATIC ROUTING

As the name suggests, static routing protocols have fixed routing. A routing table is calculated and uploaded to the UAVs before flight, and it is not possible to update or modify during their operation. This routing protocol is not dynamic and is fault-intolerant [60].

a: DATA-CENTRIC ROUTING (DCR)

Data-centric routing works based on the data. When many nodes request data at a time, these routing protocols can be used for one-to-many transmissions. This protocol provides better performance in cluster-based topologies [61].

b: LOAR CARRY AND DELIVER ROUTING (LCAD)

In this method, data is carried from the source ground station, and transmitted to destination ground station via flight, as shown in Fig. 13. This method is secure, and the throughput is high. However, the main limitation of the method is that owing to long distances, and transmission delay may be high. To decrease the transmission delay, a multi-UAV system may

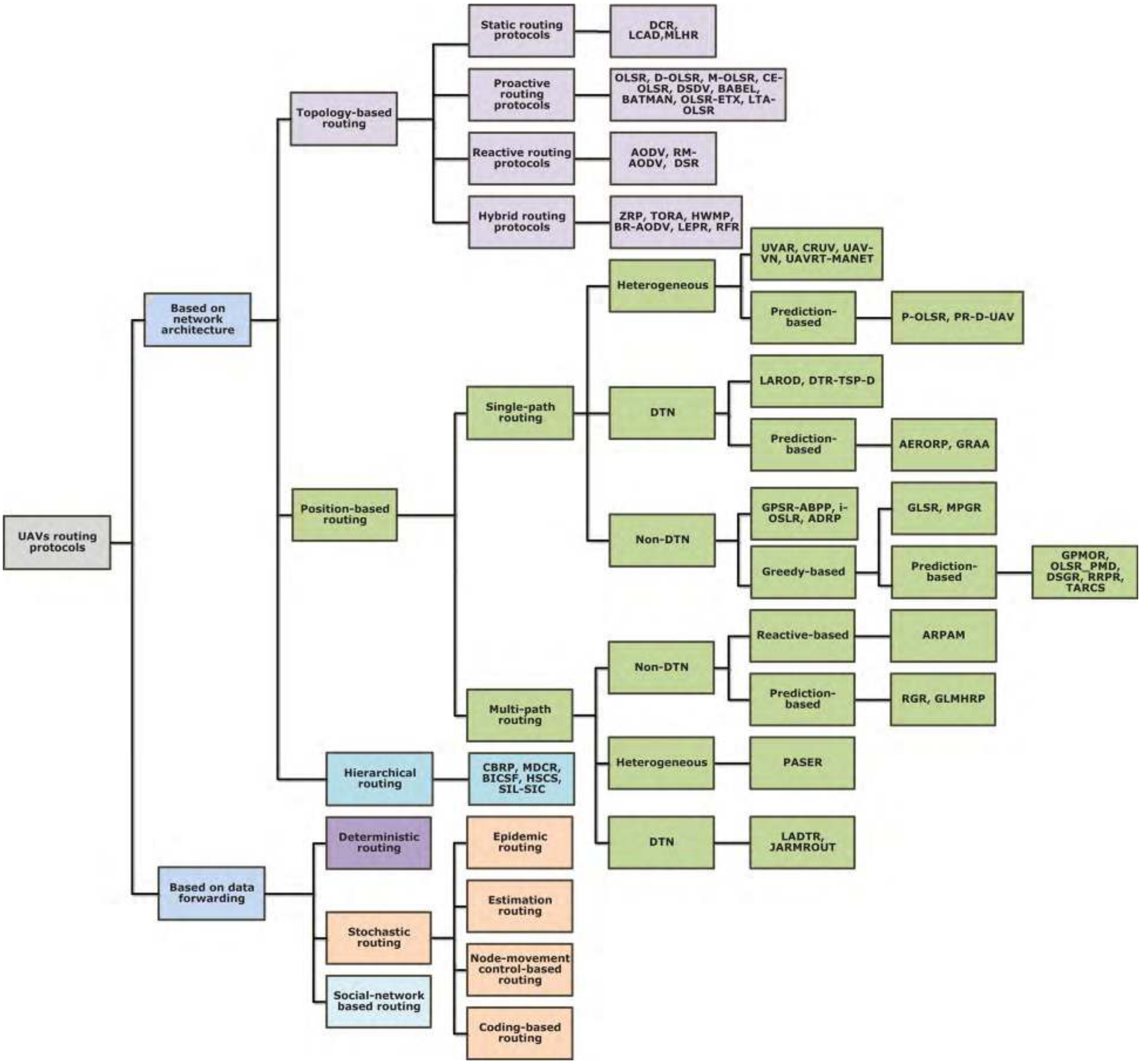

FIGURE 12. Taxonomy of routing protocols for UAV networks.

be used and that may reduce the transmission delay of the data transfer [62].

c: MULTI-LEVEL HIERARCHICAL ROUTING (MLHR)

In a hierarchical network, several numbers of clusters can perform in various operations, as shown in Fig. 14. MLHR can form a flat base structure [63]. The hierarchical architecture is used to increase the network operation area and size. UAV networks may be divided into several clusters, and only the cluster head (CH) links with another cluster group head, and as well as the ground node.

2) PROACTIVE ROUTING PROTOCOL (PRP)

PRP uses a routing table to store all the routing in the communication network. These routing tables are updated and shared periodically among the nodes. When the topology changes, tables need to update. The major advantage of PRP is it always contains the latest information. To keep updating the routing tables, routing messages need to be exchanged between all communication nodes. However, that takes too much bandwidth and makes the network unsuitable. When the network topology changes, it shows the slow response resulting in delay in the network [64].

a: OPTIMIZED LINK ROUTING (OLSR)

OSLR is one of the most used routing protocols in ad hoc networks. Multi-point relay (MPR) nodes contain the most important factors that affect the performance of OLSR. The function of the sender node is to select the MPR node, and this MPR node may cover two-hop neighbors [65].

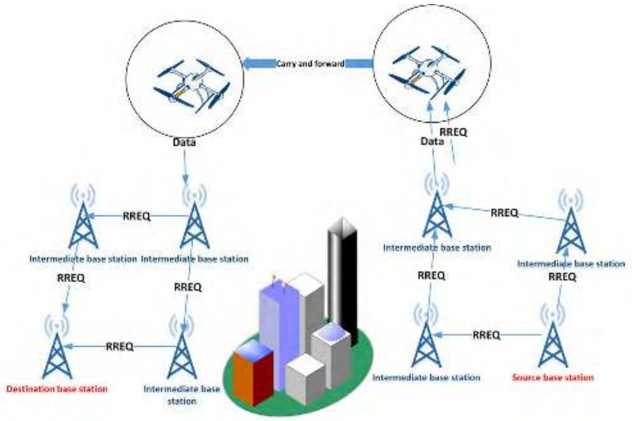

FIGURE 13. LCAD working functions.

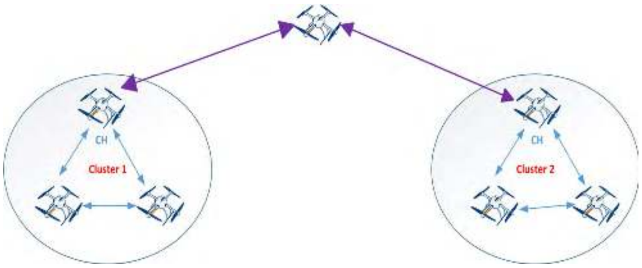

FIGURE 14. Multi-level hierarchical routing model in UAV networks.

HELLO messages are also used to find one hop and two-hop neighbors. In UAV networks, nodes change the location and interconnection link frequently. A key feature to reduce control messages in OLSR is MPR-ing. MPR nodes are a subset of nodes responsible for forwarding link state updates. This optimization to pure link state routing protocol is useful in vastly dense network environments, where the MPR method is best employed. A good number of node change control messages need to be exchanged. For the control messages, overhead is created in the networks [66]. Based on the mechanism of OLSR, several new routing protocols have been proposed, such as D-OLSR [67], M-OSLR [68], and CE-OSLR [69].

In [70], authors used OSLR routing for traffic monitoring in FANETs. The simulation results show that the OSLR routing protocol is not suited for highly dynamic and low-density FANETs networks due to large overhead. However, OSLR provides fast connection and less delay due to available routing information in the routing table. In [71], the simulation results show that OLSR outperforms AODV in terms of data delivery in UAV networks.

In [72], authors proposed a link-quality and traffic-load aware optimized link state routing protocol called LTA-OLSR to provide efficient and reliable data transmission in UAV networks. A link quality scheme was designed to differentiate link qualities between a node and its neighbor nodes by using the statistical information of received signal strength indication (RSSI) of received packets. The authors also proposed a traffic load scheme to guarantee a light-load path by considering channel contention at the MAC layer and the number of packets stored in the buffer.

b: DESTINATION SEQUENCE DISTANCE VECTOR ROUTING (DSDV)

In DSDV routing, the main mechanism is based on a small modification of the Bellman-Ford algorithm. DSDV is called a table-driven proactive routing protocol. Two types of update packets are used in DSDV, called incrementally, and full-dump. Incremental packets are transmitted when the network topology is changed; this reduces the network overhead, yet the overhead due to periodic updates remain. To avoid network loops, DSDV uses a numbered sequence to control freshness in the routes. However, it requires a large bandwidth to update the route [23].

c: BABEL

BABEL is known as a loop-avoiding distance vector protocol. It is more appropriate for unstable communication networks, operating in both IPv4 and IPv6 networks. BABEL can improve convergence rapidly to loop-free when mobility is detected. BABEL uses a metric to calculate the shortest path, and it is possible to implement BABEL within it. The limitation of BABEL is when the network topology changes, it generates more traffic for updates due to update of the periodic routing table. Rosati *et al.* have shown that BABEL fails to deliver in UAV networks in terms of average outing time, and datagram loss rate [73].

d: BETTER APPROACH TO MOBILE AD HOC NETWORK (BATMAN)

BATMAN is a comparatively fresh proactive routing protocol for ad hoc networks. Using both single-hop, and multi-hop, BATMAN proactively maintains the information about the existence of all communication nodes. The next hop neighbor is quickly recognized, which is used to communicate with the destination node. The BATMAN method is useful to find out the best next hop for each destination. The BATMAN routing process is very fast because it does not calculate the complete route. BATMAN shows good performance in terms of data rate and packet loss. The packet sizes in BATMAN is very small because it can contain only carry a limited amount of information.

In [74], a simple pragmatic routing protocol called BATMAN is presented as a response to the shortcomings of OLSR together with performance comparison. The experiment was conducted 7 × 7 grid of closely spaced nodes. Performance analysis shows that BATMAN outperforms OLSR in terms of throughput, delay, and routing overhead. The experimental result shows that, as the network grows, OLSR needs to send the entire route topology in topology update messages. BATMAN, does not embed any routing information in the routing packets and therefore does not grow rapidly at all.

e: OPTIMIZED LINK ROUTING WITH EXPECTED TRANSMISSION COUNT (OLSR-ETX)

In [75], authors claim that OLSR can suit for rapid mobility and dynamic topology changes. Authors applied GPS for calculating link expiration time. The key idea is to select the most suitable relay node by using multiple metrics and residual energy of nodes. The improved OLSR with expected transmission count (OLSR-ETX) performs better than the traditional OLSR in terms of packet transmission, end-to-end delay, and overhead.

3) REACTIVE ROUTING PROTOCOL (RRP)

RRP is an on-demand routing protocol [76]. A route between a pair of nodes is stored when they are communicating between themselves. The main design objective of RRP is to overcome the overhead problem of proactive routing protocols. During the routing process, high latency may appear owing to the long time needed in finding the route. RRP has two categories: one is source routing, and another one is hop-by-hop routing. In the case of source routing, the packet carries the complete source-to-destination address so that the intermediate nodes can easily forward the packets based on the information. Another hand hop-by-hop routing protocol simply carries the destination address, and next hop address in the packet. To forward the data, an intermediate node is responsible for maintaining the routing tables.

a: AD-HOC ON-DEMAND DISTANCE VECTOR (AODV)

AODV is a hop-by-hop reactive routing protocol, as shown in Fig. 15. It determines the route from source to destination only when the source initiates, and keeps it as long as the source wishes. To discover the destination, a route request (RREQ) packet is broadcasted by the source node [77]. The function of intermediate nodes is not only forward RREQ but also update themselves with the source information. A route reply (RREP) packet contains the number of hops required to reach the destination. A route error packet (RERR) message is generated in case of an invalid route to inform the source node about the link failure so that that source can restart the route discovery. AODV adjusts the dynamic link condition, memory overhead, and low network utilization. Because of searching for the new destination, it suffers a latency issue.

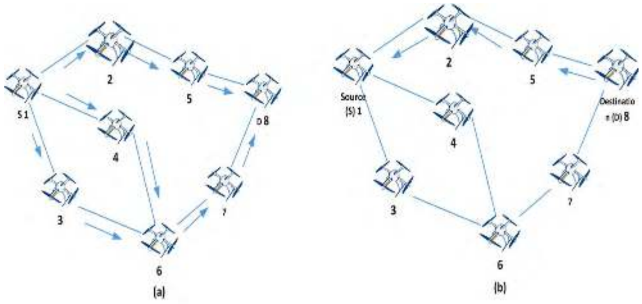

FIGURE 15. AODV routing protocol: (a) propagation of RREQ (b) RREP's path to the source.

In [78], authors used AODV routing in FANETs to examine the network connectivity. The simulation results show that the AODV protocol adapts quickly to changing network connection with a low network overhead and it achieves good network connectivity with high packet delivery ratio.

b: RADIOMETRIC AD-HOC ON-DEMAND DISTANCE VECTOR (RM-AODV)

RM-AODV protocol has been proposed by the IEEE 802.11s standard [79]. When mesh protocols (MPs) are mobile and designed to work at layer 2 with MAC address in the place of layer 3, RM-AODV is perfect in this case. RM-AODV removes the difficulty of the path determination from the upper layers so that they see all UAVs a single hop away. The path cost metric of the protocol reflects both the link quality and the number of resources consumed when a given frame is transmitted over a particular link.

c: DYNAMIC SOURCE ROUTING (DSR)

DSR has been mainly designed for multi-hop wireless mesh ad hoc networks of mobile nodes. DSR allows networks to be self-configuring, and self-organizing without any existing network infrastructure, as shown in Fig. 16. In DSR, the source node is responsible for broadcasting an RREQ to its neighbor nodes. There may be many route request messages in the communication network. For this reason, the source node adds a destination request ID to avoid any mix-ups. Route repair method is used when the source node is not capable of using its present route due to changes in network topology. In [80], authors present that to find a new route in UAV networks can be frustrating.

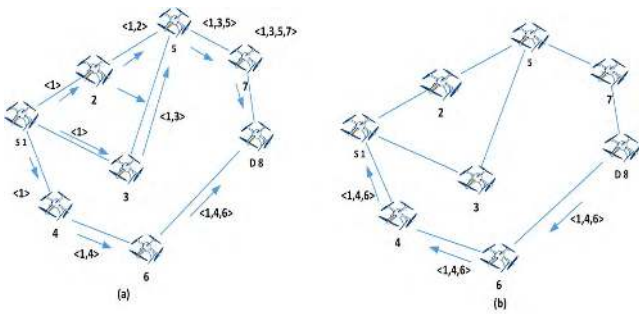

FIGURE 16. (a) Building record during route discovery, and (b) propagation of route reply with the record.

4) HYBRID ROUTING PROTOCOL (HRP)

To minimize the overhead problems in proactive and reactive protocols, hybrid routing protocols are introduced: RRP needs more time to discover routes, whereas PRP has a large overhead of control messages. HRP is suitable for the large-scale networks that may have several sub-network areas, where intra-zone routing uses PRP and inter-zone uses RRP [59].

a: ZONE ROUTING PROTOCOL (ZRP)

As its name suggests, ZRP is based on the concept of zones [81]. Every node has a different zone. A zone is defined as a set of nodes. The routing inside a zone is called as an intra-zone routing, which uses ZRP. Sources can start data communication instantly if the source and destination are in the same zone. ZRP is used when data packets need to be sent outside of the zone, which is called inter-zone routing.

b: TEMPORARILY ORDERED ROUTING ALGORITHM (TORA)

TORA is for multi-hop networks where routes only maintain information about the adjacent routers. The key purpose here is the highly dynamic mobile computing network limits the propagation of control message by minimizing the reactions to topology changes. From the source to the destination node, it makes, and maintains a directed acyclic graph (DAG), as shown in Fig. 17. To reduce the overhead, linger routes are often used, and generally, it does not use the shortest path solutions. In the case of a broken link, it prefers quickly finding new routes to increase network adaptability [82]. The advantage of TORA is it is a loop-free and multipath routing method to forward data.

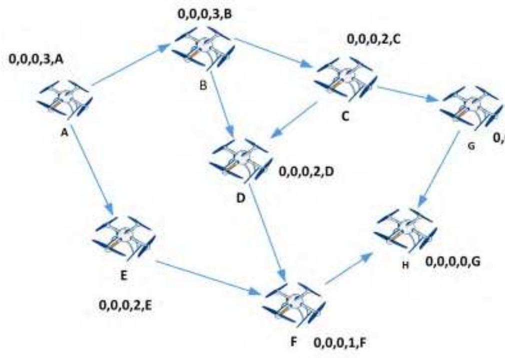

FIGURE 17. **Establishment of DAG in TORA.**

c: HYBRID WIRELESS MESH ROUTING PROTOCOL (HWMP)

The IEEE 802.11s standard proposes HWMP comprising a proactive tree-based routing protocol. HWMP is used for path selection. An HWMP protocol is used for video surveillance applications in multi-hop networks [83].

d: ON-DEMAND ROUTING WITH BOIDS OF REYNOLDS PROTOCOL (BR-AODV)

In [84], authors presented a routing protocol called BR-AODV, which is a combination of on-demand routing and Boids of Reynolds mechanism for maintaining routing and connectivity to transmit data. In this protocol, authors applied Boids of Reynolds to cope with UAV dynamic topology change to maintain the connectivity. For on-demand message transmission between UAVs, authors choose AODV protocol that allows the UAV nodes to obtain routes if necessary. BR-AODV reduces the number of launches for the route discovery process. It achieves better performance compared to AODV in terms of packet delivery ratio, end-to-end delay, and packet loss.

e: ESTIMATION-BASED PREEMPTIVE ROUTING (LEPR)

In [85], authors presented a routing protocol called link stability estimation based preemptive routing (LEPR) for FANETs, which is based on the AODV routing protocol. Authors applied link stability metric in designing LRPR, where GPS provides the node location information. Link quality, safety degree, and node mobility prediction are also taken into account. During the route discovery process, multiple link-disjoint paths are considered. LEPR reduces the number of broken paths and end-to-end delay.

Table 2 shows the summary of topology-based protocols and limitations in UAV networks. Static routing protocols are simple, and easy to configure, but are not suitable for dynamic topologies, not scalable, and prone to link breakage. Proactive routing protocols store the latest information about the routes, makes it is easy to choose the route path, and they have less transmission delay. However, they suffer from large overhead for maintaining tables up-to-date and have slow reaction to topology change. Reactive routing protocols overcome the overhead problems, high latency, and overhead due to large header size. Hybrid routing protocols are suitable for large-area networks but are difficult to implement in dynamic networks.

f: REACTIVE FLOODING ROUTING (RFR)

In [86], authors presented a reactive routing protocol and compared it with link state routing. The reactive flooding routing (RFR) is proposed for precision agriculture scenario, where sudden climate changes have an important issue on crops and cultivation quality. UAVs carry a special sensor and transmit the sensed information to farmers. The reactive-based approach performs well in terms of packet delivery ratio.

B. POSITION-BASED ROUTING

Position-based routing protocols are based on the knowledge of geographical positions, where GPS can define nodes. This routing is perfect for highly dynamic UAV communication networks. Position-based routing can be classified into two categories: single-path-based, and multi-path-based. Both single- and multi-path-based routing protocols are categorized further into heterogeneous networks, delay-tolerant networks (DTNs), and non-delay-tolerant networks (Non-DTNs).

1) SINGLE-PATH HETEROGENEOUS ROUTING

UAV protocols preserve the interaction between the UAV and various other mobile nodes that are nodes are fixed. Its major benefit is that it can extend the coverage of the sub-network located on the ground, and the ground fixed nodes to provide a reliable backbone network that can handle high bandwidth.

TABLE 2. Advantages and disadvantages of topology-based routing protocols in UAV networks.

Protocol	Advantages	Disadvantages
Static routing		
DCR	One-to-many transmission in UAV networks	Network overhead due to query and response
LCAD	Maximum throughput and security	Delivery delays
MLHR	Suitable for large-scale networks	CH becomes the single point of failure, capacity, and energy issue at CH
Proactive routing		
OSLR	Possible to use link quality extension	High overhead and routing loops
D-OLSR	Low overhead.	Require more multipoint relay (MPR)
M-OLSR	Not suitable for high-speed networks.	Higher routing overhead.
CE-OLSR	Suitable for high mobility network and higher throughput.	The possibility of collisions in the network.
DSDV	Less overhead, and avoids loops	Consumes large bandwidth, higher overhead
BABEL	Average outage time	Higher overhead, and more bandwidth
BATMAN	Less packet loss in the network	Packet loss issue
OLSR-ETX	Suitable with high mobility network.	Higher end-to-end delay
Reactive		
AODV	Increase in network bandwidth	Delay in route discovery, and higher bandwidth
RM-AODV	Can handle more bandwidth, and suitable for video surveillance	Layer 2 protocol MAC-based
DSR	More suitable for the large-area networks	Scaling problem
Hybrid routing		
ZRP	Improves the efficiency of globally reactive route query and reply	Radius is an important factor
TORA	Loop-free, and supports multiple routing structures	May produce temporary invalid results
HWMP	Suitable for video surveillance	Difficult to deploy in dynamic networks
BR-AODV	BR-AODV routing is suitable for forest fire surveillance.	Not suitable for a large-scale network.
LEPR	Support low link breakages.	Require high time to get a new router.
RFR	Consume less energy with compared link state routing	High overhead

a: UAV-ASSISTED VANET ROUTING PROTOCOL (UVAR)

After modifying a few VANET routing protocols, it may be used in UAV networks. Oubbati *et al.* proposed UAV-assisted VANET routing protocols [87]. These protocols try to address part of the connectivity-based traffic density-aware routing protocols. UVAR works based on four parameters: traffic density, distance between the nodes, connectivity, and the distributions of vehicles. These four parameters are used to exchange HELLO packets between the vehicle nodes. When the ground network is sparsely connected, UVAR overcomes the existing issues and delivers alternative solutions. To find the geographic location between the source and destination, the Dijkstra algorithm is used. UVAR can estimate the number of vehicles in each segment, which is used for data delivery. In addition, UVAR can act like as a relay when the network is on the ground. Moreover, it provides the road guidelines and supports traffic management.

b: CONNECTED-BASED TRAFFIC DENSITY AWARE ROUTING PROTOCOL (CRUV)

CRUV proposed by Oubbati *et al.* [88] performed better than [89], [90]. HELLO packets exchanged between the vehicles are periodic. These exchanges are used to find the most connected segments among the neighboring segments. For efficient routing decisions, UAVs exchange this information with the other nodes. If there is a connected segment, the source vehicle selects the UAV to which to deliver the data. Fig. 18 shows the source-to-destination vehicular data packet-sending scenario. The major advantage of CRUV is that when the current vehicle cannot find the connected segment, UAVs assist it by finding a connected segment for it.

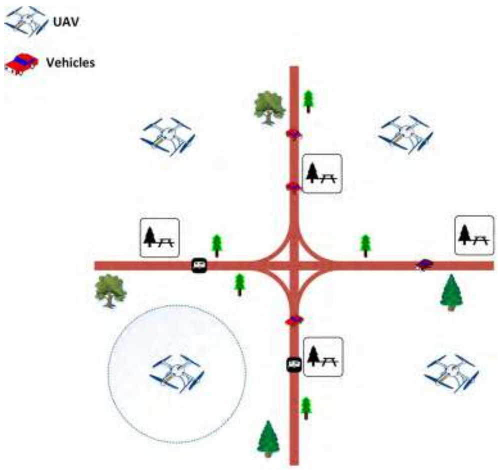

FIGURE 18. CRUV working functions.

c: UAV-AIDED VEHICULAR NETWORKS (UAV-VN)

In [91], authors address the path availability problem in the vehicular network using UAVs. In the vehicular network, path availability depends on the density and cooperation of vehicles. The authors used the advantage of UAV mobility and considered UAVs as an SCF node to enhance the availability of path connectivity. SCF enables UAV to assist the ground vehicles in the process of data delivery to the roadside unit (RSU) as shown in Fig. 19. The simulation results show that path connectivity is improved by using UAV-VN.

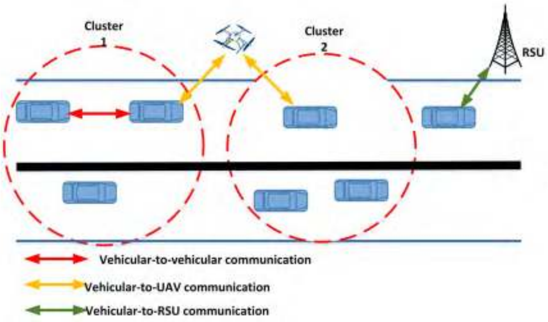

FIGURE 19. Enhance connectivity via SCF UAVs.

d: UAV RELAYED TACTICAL MOBILE AD HOC NETWORKS (UAVRT-MANET)

In [92], authors present a routing protocol to implement UAV-aided relay in MANETs, The relay node is used to make an alternative temporary path in routing. Due to high dynamics of nodes, network partitioning happens frequently in tactical ad hoc networks. To avoid this problem, relay node is one of possible solutions by connecting the partitioned networks and providing alternative backup paths temporarily. The path via UAV relay nodes is controlled according to the type of communication, service, and source-destination pair. The UAV-aided solution is effectively used for rapid coverage. The simulation results show the UAVRT-MANET performs better than typical geographical routing protocols. In addition, the authors proposed admission control based on packet prioritization to avoid network traffic congestion and link breakage. During the link breakage between the MANET nodes, it is possible to use a UAV as an alternative routing path. The total capacity of UAV is classified as the two categories of reserved and contention schemes. The reserved scheme is for link breakage and the contention scheme is for packet forwarding during the network congestion.

e: PREDICTIVE-OPTIMIZED LINK STATE ROUTING PROTOCOL (P-OSLR)

P-OSLR [93] is used in UAV networks based on the prediction from GPS information about the link quality. Rosati *et al.* proposed P-OSLR. The original OSLR is modified, and a HELLO packet is generated to share the geographical position. With this process, each node knows the position of its neighboring nodes. A metric, called expected transmission count is used to calculate a factor. Compared to the OLSR, this protocol exploits the GPS information of the UAVs. P-OSLR may be used in the highly dynamic UAV networks.

f: PREDICTIVE ROUTING FOR DYNAMIC UAV NETWORKS (PR-DUAV)

In [94], authors proposed an optimal routing algorithm for UAV networks called PR-DUAV, which is based on Dijkstra's shortest path algorithm. The key idea of the PR-DUAV routing protocol is to combine the predicted locations of intermediate nodes during transmission session and path selection. In PR-DUAV, the authors modified the Dijkstra's shortest path algorithm by incorporating predicted pairwise distances into the path selection criterion. The Dijkstra's algorithm is chosen because it reduces the amount of computation in comparison to other shortest path algorithms. The PR-DUAV algorithm involves starting from the source node at time 0 and finding the next intermediate node considering the predicted network topology. Once the packet reaches the second node, the network topology is updated based on the actual pairwise distances. Then, the problem reduces to finding the optimal path from the second node to the destination using a degraded contact graph excluding the source node. At each step, the edge metrics are calculated by incorporating predicted node locations. The simulation results show that the PR-DUAV routing enhances delivery path and reduces end-to-end delay. The PR-DUAV routing algorithm prolongs the network connectivity by excluding the links that are likely to get disconnected due to exceeding the predefined communication range.

2) SINGLE-PATH DELAY-TOLERANT NETWORK ROUTING (DTN)

Owing to the high degrees of node mobility, some nodes may have to disconnect. DTN protocols handle technical issues, such as disconnection in the communication network. When connectivity is lost, these protocols use the store-carry-and-forward technique. This method stores the data packets until they meet with other nodes. The method sees decreased overhead because it does not use any additional control packets. The most used protocols are location-aware routing for opportunistic delay tolerance (LAROD) [95]; aeronautical routing protocol (AeroRP) [96] proposed by Jabbar and Peter, *et al.*, which is a geographical delay tolerant routing protocols; and geographic routing for aircraft ad hoc networks (GRAA) [97], as proposed by Hyon *et al.*, which is geographic routing protocol based on GPRS.

a: LOCATION-AWARE ROUTING FOR OPPORTUNISTIC DELAY-TOLERANT NETWORKS (LAROD)

LAROD was proposed by Kuiper *et al.* [95], which is a delay-tolerant geographical routing protocol that is based on the combination of greedy forwarding and store-carry-and-forward methods. The beaconless strategy may be used to decrease the overhead with the help of network management. When a source UAV "S" desires to transmit a data packet to a destination UAV "D," it broadcasts it to the neighboring nodes, as shown in Fig. 20.

A timer starts whenever an intermediate node receives the data packets. The source UAV overhears transmission and deducts its information. If no transmission occurs, the source UAV periodically broadcasts the data packet until a node becomes available in the network. Store-carry-and-forward methods hold the data packets until it meets with the next nodes; in this case, greedy forwarding may be used to resume the delivery of the data packets delivery until they reached their destination UAV. An acknowledgment (ACK) packet

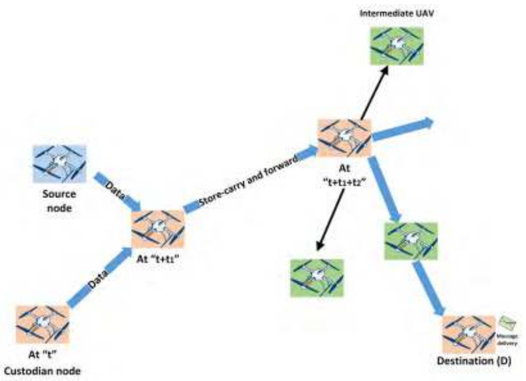

FIGURE 20. **LAROD working principle.**

is then broadcast from the destination to the source when the data packets have successfully reached the destination node. Store-carry-and-forward methods provide a high delivery ratio in networks. However, for its energy consumption, LAROD is not suitable for mini-drones.

b: DEADLINE TRIGGERED PIGEON WITH TRAVELLING SALESMAN PROBLEM (DTP-TSP-D)

DTP-TSP-D was proposed by Barroca *et al.* [98], which is a delay-tolerant relay routing protocol. In DTP-TSP-D, the ground node can make communication with flying UAVs to forward messages from one location to another location. In this routing protocol, a UAV acts as a ferrying node. Genetic algorithm is used to deliver the message on time. The performance study in [98] shows that DTP-TSP-D outperforms the traditional routing algorithm in terms of packet delivery ration and average delay. In this DTN routing, message delivery deadline is taken into key consideration.

3) SINGLE-PATH NON-DELAY-TOLERANT NETWORK ROUTING

Non-DTN routing protocols may be used where the density of node is high in a network. They are classified into reactive-based and greedy-based protocols. Reactive-based protocols need to have full path to the destination based on routing paths. Greedy-based protocols communicate data packets to the nearest neighbors to reach the target destinations. In the case of no neighbors, however, the data delivery may fail, and a recovery approach may be required.

a: GPSR-ADAPTIVE BEACON AND POSITION PREDICTION (GPSR-ABPP)

In [99], authors proposed a routing protocol based on greedy perimeter stateless routing with adaptive beacon scheme. In pure geographic routing, beacon signal should be sent periodically to maintain the precision routing selection. However, it creates extra overhead in the network. To address high overhead issue, the authors proposed adaptive beacon scheme, which adjusts the beacon signal frequency and predicts the future position of UAVs in highly mobile networks.

b: IMPROVED OPTIMIZED LINK STATE ROUTING PROTOCOL (i-OLSR)

In [100], authors integrate GPS with OLSR routing protocol to minimize the route discovery process. Due to high speed of UAVs, network topology changes frequently; therefore, finding a new position of UAVs is a challenging task. In the improved optimized link state routing protocol (i-OLSR), link quality estimation and speed weighted expected transmission count (ETX) are measured to perform mobility model. The simulation results show that i-OLSR outperforms the traditional OLSR routing in terms of throughput.

c: ADAPTIVE DENSITY-BASED ROUTING PROTOCOL (ADRP)

In [101], authors proposed adaptive density-based routing called ADRP for FANETs. The aim of ADRP is to increase the data forwarding efficiency by forwarding adaptively. The simulation results indicate that ADRP outperforms AODV routing in terms of packet delivery, end-to-end delay, and routing overhead. The nodes with few neighboring nodes forward the route request packets with higher probability, which reduce end-to-end delay and rebroadcasting.

4) SINGLE-PATH -GREEDY-BASED NON-DELAY TOLERANT ROUTING

a: GEOGRAPHIC LOAD SHARE ROUTING (GLSR)

Geographic load share routing (GLSR) [102] is another geographic routing protocol for UAVs, proposed by Medina *et al.*, which can use multiple paths at a time between the source, and the destination. In addition, Mobility predication-based geographic routing (MPGR) [103] based on geographic position for inter-UAV networks, proposed by Lin *et al.*, uses the Gaussian distribution function to detect the mobility of UAVs.

b: GEOGRAPHIC POSITION MOBILITY-ORIENTED ROUTING PROTOCOL (GPMOR)

GPMOR, proposed by Lin *et al.* uses mobility prediction method the Gauss–Markov mobility model to be exact for routing [104], [105]. Here, all UAVs know their position via GPS and exchange their geographical position with neighboring UAVs. GPMOR also predicts the movements of the neighbors, and deduces their new positions, as shown in Fig. 18. In Fig. 21, UAV "S" selects the neighbor UAV "C" for data delivery because UAV "C" is not the best one for further movement.

c: OPTIMIZED LINK STATE ROUTING WITH MOBILITY AND DELAY PREDICTION (OLSR_PMD)

In [106], authors presented an improved version of OLSR routing protocol called OLSR_PMD for UAV networks, which is based on node mobility and delay prediction mechanism. In OLSR_PMD, authors applied the Kalman filter algorithm for selecting stable neighbor nodes as a multi-point relay (MPR). Authors considered queuing delay as a routing metric and devised a cross-layer queuing delay prediction

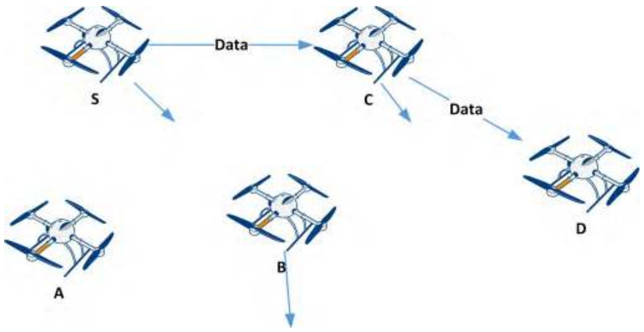

FIGURE 21. Data delivery process in GPMOR.

mode for reducing end-to-end delay and balancing load between nodes.

d: DISTANCE-BASED GREEDY ROUTING (DSGR)

In [107], authors presented a distance-based greedy routing protocol (DSGR) for UAV networks. DSGR aims to reduce route setup time in UAV networks. It relies on local forwarding decision and does not require route setup phase. The total network is divided into several grids. The position of each node is measured. In DSGR, however, the predicated locations are the actual locations mixed with normal distributed prediction. DSGR performs better than conventional Dijkstra's shortest path algorithm.

e: ROBUST AND RELIABLE PREDICTIVE ROUTING (RRPR)

In [108], authors presented a robust and reliable predictive-based routing called RRPR for FANETs. In RRPR, omnidirectional and directional transmission are used together with dynamic angel adjustment. Unicast and geocast routing schemes are used to get the location and trajectory information. The simulation results show that the RRPR routing increases the route setup success rate as well as active-path lifetime.

f: TOPOLOGY-AWARE ROUTING CHOOSING SCHEME (TARCS)

In [109], authors proposed a topology-aware routing protocol called TARCS for FANETs. Topology change is an important factor in FANETs. In TARCS, moving nodes sense the periodical change of surrounding network topology. The simulation results show that TARCS can adapt to rapid topology change in FANETs. The proper routing path is selected on the basis of new topology. The authors also proposed a mobility metric named topology change degree (TCD) to describe the topology change in FANETs.

5) MULTI-PATH NON-DELAY-TOLERANT NETWORK ROUTING

Aeronautical mobile ad hoc networks (ARPAM) [110] proposed by Lordankis *et al.*, which is based on the geographical position. Numerous Non-DTN routing protocols have been proposed, such as reactive greedy reactive (RGR) [111]; multi-path Doppler routing (MUDOR) [112], proposed by Sakhee *et al.*, which uses the most stable path with the longest lifetime.

a: REACTIVE GREEDY REACTIVE PROTOCOL (RGR)

RGR is widely used in UAV networks. If there is no route to the target destination, then the source node needs to begin an on-demand path to continue the communication with the target destination node. This routing protocol was proposed by Shirani *et al.*, and it is based on the combination of topology-based, and classic delivery-based routing [113]. In topology-based routing, on-demand routing paths are created using AODV, and a classic delivery-based path is based on greedy geographic forwarding (GGF) [114].

b: GEOLOCATION-BASED MULTI-HOP ROUTING PROTOCOL (GLMHRP)

In [115], authors proposed a geolocation-based multi-hop routing protocol (GLMHRP) for FANET. Authors aim to maintain the robust connectivity between ground stations to flying UAVs. In this proposed multi-hop routing algorithm each UAV broadcast its routing information after a time interval. This routing information contains the UAV nodes geolocation, speed, and direction. The decision of data forwarding is based on greedy manner. A node selects the next hop based on geolocation of neighbor's node; this geolocation contains node speed, direction, and time information of UAVs. Due to the use of navigation node can get the latest information about nodes, which makes impacts the routing performance.

6) MULTI-PATH HETEROGENEOUS ROUTING

In this subsection, multi-path heterogeneous routing protocols are presented.

a: POSITION AWARE, SECURE, AND EFFICIENT MESH ROUTING (PASER)

PASER is considered as a secure routing protocol for UAV networks, as proposed by Sbeiti *et al.* [116] Only within the valid nodes, PASER maintains perfect routing paths. It can discover malicious nodes that do not belong to the network quickly. PASER uses a routing key to join a new node in the network. The ground station then decides the appropriate actions for the malicious node. In the network, a requesting node broadcasts RREQ packets on behalf of the routing side, as illustrated in Fig. 22. The nodes that receive the RREQ packets are registered and known to be valid nodes. The destination node transmits RREQ packets to establish the connection. PASER is more suitable for highly dynamic UAV networks.

7) MULTI-PATH DTN ROUTING

a: LOCATION-AIDED DELAY TOLERANT ROUTING (LADTR)

In [117], authors presented a location-aided delay tolerant routing protocol (LADTR) in UAV networks for post-disaster operation. In LADTR, store-carry-forward (SCF) technique

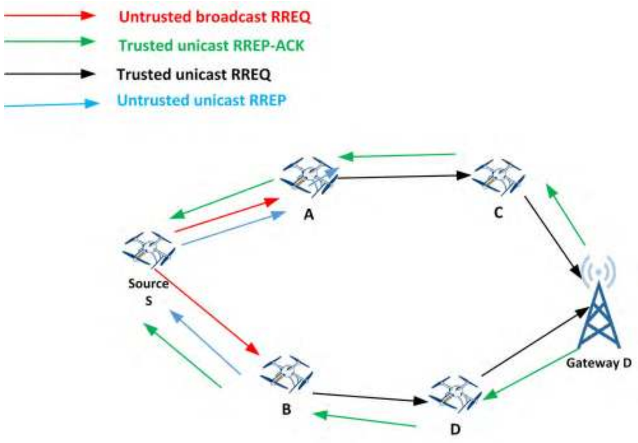

FIGURE 22. PASER working mechanism.

is exploited for DTN forwarding. Ferrying UAVs with SCF is introduced in LADTR, which increase the performance of the routing protocol. Ferrying UAVs also increase the number of node connection paths between the searching UAVs and the ground station, as illustrated in Fig. 23. It is shown in [116] that the packet delivery ratio, average end-to-end delay, and overhead of LADTR are significantly improved in comparison to the conventional approaches.

FIGURE 23. LADTR routing mechanism.

b: JAMMING-RESILIENT MULTIPATH ROUTING (JARMROUT)

In [118], authors presented a jamming-resilient multipath routing protocol called JarmRout because the intentional jamming and disruption or isolated and localized failures interrupt the overall network performance of FANETs. The JarmRout relies on a combination of three major schemes that are link quality scheme, traffic load scheme, and spatial distance scheme. The link quality scheme is proposed to differentiate link qualities between a node and its neighbor nodes by using the statistical information of received signal strength indication (RSSI) of received packets. In the traffic load scheme, the authors considered the channel contention information at the MAC layer and the number of packets stored in the buffer. The spatial distance scheme measures the spatial separation distance of multiple paths to ensure the maximally spatial node-disjoint multipath between source and destination nodes. Simulation results in [118] show that the JarmRout increases packet delivery ratio, decreases latency, and reduces end-to-end communication outage rate without introducing extra communication overhead.

The advantages and disadvantages of the position-based routing protocols in UAV networks are summarized in Table 3.

C. CLUSTER-BASED ROUTING PROTOCOLS

In this section, cluster-based routing protocols are described. In [119], authors proposed swarm intelligence topology management in FANTs for cluster-based network.

1) CLUSTER-BASED ROUTING PROTOCOL (CBRP)

UAVs can be organized with cluster-based networks. Proposed by Luo *et al.*, CBRP is based on the geographic area, which is divided into several square grids [120]. Each grid contains a cluster member, of which one UAV will act as a CH, as shown in Fig. 24. Cluster member UAVs deliver the data to CH for transfer to the base station. The benefit here is the lower overhead, and it does not need to discover routes, and thus, saves routing tables; CH is the one responsible for data routing.

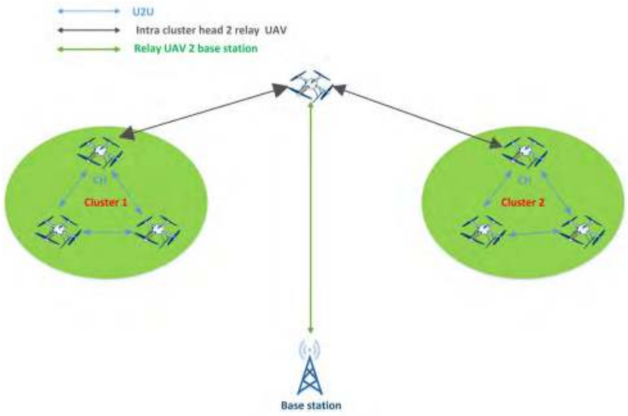

FIGURE 24. Network model for cluster-based routing.

To optimize the routing operation, and the flooding of messages, clustering schemes may be used. It can be integrated into any reactive, proactive, or geographic ad hoc routing protocol. It is suitable for both short- and long-range transmission. Clustering also minimizes the on-demand route discovery traffic by using GPS for geographic location. Furthermore, it uses ''local repair'' to reduce route acquisition delay and new route discovery traffic.

2) MODULARITY-BASED DYNAMIC CLUSTERING RELAY ROUTING PROTOCOL (MDCR)

In [121] authors presented the modularity-based dynamic clustering relay (MDCR) on the modified Louvain method for UAVs aided communication. Proposed routing ambitions to save the transmit power of the mobile devices and energy efficient UAVs aided mobile communication. In the process of

TABLE 3. **Advantages and disadvantages of position-based routing protocols in UAV networks.**

Protocol	Advantages	Disadvantages
UVAR	As vehicles are well distributed, each segment has good data delivery; can also act as a relay	Delays due to use of carry-and-forward method
CRUV	UAVs can use as relay when the network is poorly dense	Does not consider real distribution and delivery delay
UAV-VN	Enhance path connectivity	Optimal placement of UAV is key issue
UAVRT-MANET	Resolve the link breakage and contention	Finding new route may cause delay in network
P-OLSR	Adapted to highly dynamic network	Sudden disconnect of node can occur
PR-DUAV	Reduced end-to-end delay	Takes long time in the route process due to blind search in Dijkstra algorithm
LAROD	High delivery ratio, lower overhead, and low energy consumption	High delay for delivering using store-carry-forward, and higher overhead
DTP-TSP-D	High packer delivery ratio.	End-to-end delay may increase due to find new path.
AeroRP	High packet delivery ratio (PDR), accuracy, and low overhead	Higher delay due to ferrying model
GRAA	GRAA provides high delivery ratio	Has packet loss issues
GPSR-ABPP	Reduce beacon overhead	Low localization accuracy in high mobile network
i-OLSR	Improved node localization	Complex mobility model
ADRP	Reduce end-to-end delay and overhead	Route discovery time will be longer in dynamic network
GLSR	Average end-to-end delay and high throughput	Packet loss may occur
MPGR	Reduce the delay and packet loss and Fast router decision process makes less delay and less packet loss.	Have a problem in a hop selection and Ignore the use of the link expiration time to find the next hop.
GPMOR	High delivery ratio, and less delay	Has packet loss issues
OLSR_PMD	Delay sensitive routing.	Has more routing overhead.
DSGR	Reduce end-to-end delay	Complexity of algorithm is huge.
RRPR	Increase route setup success rate	Difficult to measure the node angel
TARCS	Sense the rapid change in topology	Route selection may longer
ARPAM	Decreased delay for delivery	Not suitable for high mobility network
RGR	Improves on the delivery ratio, and end-to-end delay	Geographical locations of the next hop are not updated regularly and has packet loss issues
MUDOR	High data packet delivery	Routing path may not stable, and has high overhead
GGF	High delivery ratio, and less end-to-end delay	Packet loss occurs due to high mobility
GLMHRP	Decrease the effect of high mobility and routing void	Low scalability
PASER	Provide security, and suitable for highly dynamic networks	Higher overhead, and delay during route discover
LADTR	High throughput, less end-to-end delay and lower overhead.	Consider only 2D network scenario.

clustering, after forming the dynamic clusters, the UAVs are relocated to the positions vertically projected on the centroids of clusters as shown in Fig. 25. Each UAV serve a cluster of mobile devices, and mobile devices and UAVs are denoted as $\{x_v^m, y_v^m, 0\}$ and $\{x_n^u, y_n^u, z\}$ respectively. In the proposed clustering scheme, a network is considered as a graph-based clustering approach. Each area of the network is marked as an adjacent matrix such as A and size of A is about $V \times V$ with all entries being initialized to zero.

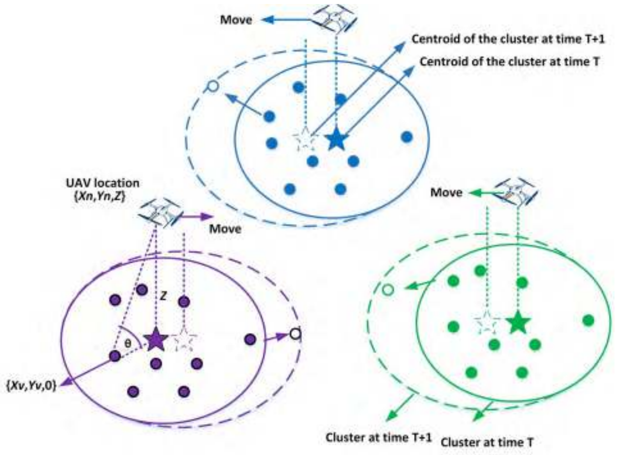

FIGURE 25. UAV aided cluster-based mobile communication system.

Modularity is considered as a factor in clustering performance by assessing and comparing the closeness inside and between the clusters of a given network graph. When network graph is slowly varying due to moving devices. Two types of operating proposed in modified Louvain method. The purpose of recurring operation denotes to apply the modified Louvain method every time when the network is changed, and differential operation mentions to apply the modified Louvain method only for considering the incremental dynamics. After the cluster formed the UAVs, need to be relocated to the new position. The new position is vertically projected on the corresponding centroids of new clusters. For saving energy, UAVs need to minimize the travel distance. Greedy approach use for schedule which UAV is relocated to which cluster. A new distance matrix conduct, where its (n, j) entry records the distance between the nth UAV's current location and destination of the jth new cluster.

3) BIO-INSPIRED CLUSTERING SCHEME FOR FANETs (BICSF)

In [122], authors proposed a bio-inspired clustering scheme for FANETs called BICSF, which uses the hybrid mechanism of glowworm swarm optimization (GSO) and krill herd (KH). The BICSF scheme uses energy-aware cluster formation and cluster head election based on the GSO algorithm. An efficient cluster management algorithm was also introduced using the behavioral study of KH. For route selection, the authors proposed a path detection function based on the weighted residual energy, the number of neighbors, and distance between UAVs. The performance of BICSF was evaluated in terms of cluster building time, energy consumption, cluster lifetime, and the probability of delivery success with the clustering algorithms based on grey wolf optimization and ant colony optimization.

4) HYBRID SELF-ORGANIZED CLUSTERING SCHEME (HSCS)

In [123], authors presented a hybrid self-organized clustering scheme called HSCS for drone-based cognitive IoT. The clustering scheme exploits a combination of glowworm swarm optimization (GSO) and dragonfly algorithm (DA). The HSCS scheme contains cluster formation and cluster head selection mechanism based on GSO. Furthermore, the authors proposed an effective cluster member tracking methodology using the behavioral study of DA, which ensures efficient cluster management. For improving the network stability, the cluster maintenance is performed by a mechanism to identify dead cluster members. In HSCS, the next-hop neighbor for data transmission is selected by using the route selection function.

5) SWARM INTELLIGENCE-BASED LOCALIZATION AND CLUSTERING (SIL-SIC)

In [124], authors presented swarm-intelligence-based localization (SIL) algorithm based on particle swarm optimization (PSO). The SIL algorithm exploits the particle search space in a limited boundary by using the bounding box method. Anchor UAV nodes are randomly distributed in the 3D search space, and the SIL algorithm measures the distance to existing anchor nodes for estimating the location of the target UAV nodes. The authors also proposed an energy-efficient swarm-intelligence-based clustering (SIC) algorithm based on PSO. In SIC, particle fitness function is exploited for inter-cluster distance, intra-cluster distance, residual energy, and geographic location. For energy-efficient clustering, cluster heads are selected based on improved particle optimization. In the SIL algorithm, convergence time and localization accuracy are improved with lower computational cost. According to the simulation results in [124], the SIC algorithm outperforms conventional schemes in terms of packet delivery ratio, average end-to-end delay, and routing overhead. Moreover, SIC consumes less energy and prolongs network lifetime.

D. DETERMINISTIC ROUTING PROTOCOL

In deterministic routing, further movement of a node is already known by neighboring nodes. This protocol may be considered in UAV networks because their flight is in controlled formations. If all nodes have the information of other nodes in terms of mobility, availability, and motion, then a tree approach could be designed for select paths. In the tree, the source node is considered as the root node and other nodes as child nodes. Paths are selected from the tree based on the earliest time to reach the destination node [61]. This protocol is useful when future availability and location of the nodes are known.

E. STOCHASTIC ROUTING PROTOCOLS

Stochastic routing protocols are for networks where the network behavior is unknown and random [125]. In this condition, packet delivery decision becomes important. One solution is to forward the data to the next node hoping that it is communication range. Here, historical data, mobility patterns, and other information are all considered for routing. It is a time-varying network topology protocol whose objective is to minimize the end-to-end delay by maximizing the probability of delivery at the destination. There are a few categories of stochastic routing protocols such as epidemic routing-based approach [126], estimation-based routing [127], node movement and control-based routing [128], and coding-based routing [129].

1) EPIDEMIC ROUTING-BASED APPROACH

If the mobile nodes are disconnected, the epidemic routing-based approach may be used. It is a flooding protocol where the nodes make several copies of messages and forward them to other nodes. In the place of forwarding messages to the next nodes, intermediate nodes guess the probability of each link. In this method, the node requires large buffer sizes, bandwidth, and power.

2) ESTIMATION-BASED APPROACH

Via estimation, intermediate nodes store the packet and decide when it should be forwarded to the next node. Random nodes work well for small networks, but for large networks, estimations result in large overheads.

3) NODE MOVEMENT AND CONTROL-BASED APPROACH

In node movement and control-based routing, nodes decide whether to wait for reconnection with neighboring nodes when disconnected. When a node waits for reconnection, there may be unacceptable transmission delays in the reactive case. To control the node mobility and delay, a number of approaches have been proposed. In the proactive case, message ferrying approach uses to ferry data from source to destination.

4) CODING-BASED APPROACH

Coding-based routing uses the concept of network coding, so that built-in redundant information and retransmission is avoided. This method may be employed in UAV networks, as in UAVs retransmission would require finding a new path, as disruption is the norm.

5) SOCIAL NETWORK (SN)-BASED APPROACH

When the mobility of the nodes is not random, but rather fixed, then the use of large numbers of networking protocols is not realistic. When nodes visit a place, it can store data of the visiting place in a database for further use. Using this database, the node can select paths very quickly in its subsequent attempts. This protocol is useful when UAV nodes store

TABLE 4. Comparison of routing approaches for UAV networks.

Routing approach	Routing type	Topology size	Overhead	Latency	Mobility	Bandwidth Utilization	Complexity
Static routing	Static	Small network	No	Low	Fast	Maximum	Low
Proactive routing	Dynamic	Small network	Yes	Low	Slow	Maximum	Medium
Reactive routing	Dynamic	Larger network	Yes	High	Mostly Fast	Maximum	Average
Hybrid routing	Dynamic	Small and large both	Yes	High	Average	Medium	Average
Position-based routing	Dynamic	Large network	Yes	Low	Average	Minimum	High
Hierarchical-based	Dynamic	Large network	Yes	High	Average	Maximum	High

node information, like location. SN-based routing requires higher buffer size and higher bandwidth.

VI. COMPARISON OF ROUTING PROTOCOLS

Routing protocols use several routing metrics as the basis to decide on the routing from the source to the destination. Thus, routing metrics play a vital role in the quality of a routing path [130]. Comparing routing protocols shows that all routing protocols differ considerably from each other. UAV routing protocols are categorized via common parameters, such as packet delivery ratio (PAR), average end-to-end delay, average number of hops, overhead, latency, and throughput. In addition, other properties, such as complexity, topology size, memory size, fault tolerance, bandwidth utilization, and applications need consideration. Some protocols support location detection GPS, where each node location can be identified. UAV nodes can also communicate with ground base stations to transfer certain information. In the evolution of routing protocols, various simulation tools have been used. Simulation tools are capable of simulating scenarios based on the application, and environments. Different metrics are used in the simulation of each routing protocol to analyze their behavior and compare with other routing protocols using the same performance metrics. Based on the simulations, it may be possible to analyze the strengths and limitations of the protocols.

Table 4 summarizes our comparisons of the fundamental routing protocols in UAV networks. To Reiterating the discussion in the previous section, static protocols store the routing information before flight, proactive protocols use routing tables to store the route log, reactive protocols use source-based routing, hybrid protocols contain both proactive and reactive protocols, position-based protocols use GPS to find the geographical location, and hierarchical protocols are based on clustering. We also know that static and proactive routing protocols are suitable for small-area networks. Position-based and hierarchical protocols are more suitable for large-are networks. In addition, hierarchical protocols use less bandwidth compared to all other protocols. Moreover, complexity is also an issue. Static, proactive, and reactive protocols are less complex compared to position-based and hierarchical protocols.

As shown in Tables 5 and 6, UAV routing protocols are categorized according to their delivery approaches. Routing protocols use GPS to define the geographic location. Most topology-based routing protocols do not support GPS, whereas the location service is supported by all position-based protocols. Position-based protocols used geographic position information for packet forwarding decisions, leaving the need for a routing table; the location of the neighboring nodes is sufficient to forward packets. This minimizes overhead and makes the routing protocols more scalable.

Simulation tools are used for performance tests of the protocols, as well as validation. Different simulators use different techniques that vary from one protocol to another. The mobility generator and hence the mobility of UAV nodes are different for every simulator. In addition, different routing metrics are used by different simulators; although most consider packet delivery ratios, control of packets, broadcasting, disconnections of nodes, congestion, and overhead as key performance parameters. Tables 5 and 6 provide detailed comparisons of topology- and position-based routing protocols in UAV networks, respectively.

As shown in Table 7, few field experiment of UAV routing protocols are presented. In [131], authors proposed a location-based delay tolerant routing protocol called DTN-GEO. Authors implemented routing algorithm test in field experiment. Authors used up to three quadcopters and one ground station and all copters generate data destined to the ground station. In [132], authors propose a novel adaptive hello interval scheme called energy efficient hello (EE-Hello) based on available mission-related information, such as the volume of the allowed airspace, number of UAVs, UAV transmission range, and UAV speed. In [133], authors used UAV based data mules called (UAV-DM); the performance has been thoroughly evaluated in realistic settings. In [134], authors made a field experiment of multi-UAV Ad Hoc networks, and set up a wireless multihop ad hoc network called (MUAV-AD HOC) to test the performance of multi-hop network. In [135], authors have tested swarm intelligence-inspired autonomous flocking control (SIIAFC) in UAV Networks, which is a distributed multi-layer flocking control scheme called SIMFC. SIMFC enables a follower node to autonomously follow the leader node and resolves the problems of multiple F-nodes collision avoidance. In [136], authors make a field test of multi-UAV routing (MUAV-R) for area coverage and remote sensing with minimum time.

VII. OPEN ISSUES AND RESEARCH CHALLENGES

UAV routing protocols are still in their developmental stage. The highly dynamic network routing techniques are still an open research issue. Most of the routing protocols

TABLE 5. Comparison of topology-based routing protocols for UAV networks.

Protocol	Location service	GPS	Path discovery	Single path	Multipath	Evaluation metrics*	Latency	Simulation tools	Types of network
Static routing									
DCR	☑	☒	YES	YES	NO	D	Low	NS-2	MANET/ FANET
LCAD	☑	☑	YES	NO	YES	P, T	High	NS-2	MANET/ FANET
MLHR	☒	☒	YES	NO	YES	O	-	NS-2, OMNET++	MANET/ FANET
Proactive routing									
OSLR	☒	☒	YES	NO	YES	O	Medium	OPNET, QualNet	MANET/ FANET
D-OSLR	☒	☒	YES	NO	YES	D, P	Medium	OPNET	FANET
M-OLSR	☒	☒	YES	NO	YES	P, O, D	Low	NS-2	FANET
CE-OLSR	☑	☑	YES	NO	YES	P, D	Low	NS-2	FANET
DSDV	☒	☒	YES	NO	YES	O	High	NS-2, GloMoSim	MANET/ FANET
BABEL	☒	☒	NO	NO	YES	-	Medium	NS-2	MANET/ FANET
BATMAN	☒	☒	YES	NO	YES	P, D, H	Low	-	MANET/ FANET
OLSR-ETX	☑	☑	YES	NO	YES	P, D,O	Low	NS-3	FANET
Reactive routing									
AODV	☒	☒	YES	NO	YES	P, D	Medium	OPNET, NS2, OMNET++	MANET/ FANET
RM-AODV									
DSR	☒	☒	YES	NO	YES	D	-	NS-2, OPNET, OMNET++	MANET/ FANET
Hybrid routing									
ZRP	☑	☒	YES	NO	YES	D	Low	QualNet GloMoSim	MANET/ FANET
TORA	☑	☒	YES	NO	YES	-	Low	NS-2, OPNET	MANET/ FANET
HWMP	☑	☒	YES	NO	YES	P, D	Medium	NS-2	FANET
BR-AODV	☑	☑	YES	NO	YES	P, D, O	Low	-	FANET
LEPR	☑	☑	YES	NO	YES	P, D,O	Low	NS-3	FANET
RFR	☒	☒	NO	YES	NO	E	Low	Testbed	FANET

Evaluation metrics*: P: Packet delivery ratio, D: End-to-end delay, O: Overhead, H: Average number of hops, E: Energy

proposed yet are based on those for MANETs and VANETs. However, these are not inherently suitable for UAVs as routing protocols owing to the unique characteristics of UAVs and have therefore been unable to yield good performance in UAV networks. Hence, several keys issue that have not been solved yet for existing routing protocols. Most of the existing routing protocols have not functioned well with UAV networks and cannot provide the security requirements. In this subsection, we discuss some open research issues and challenges of routing protocols for UAV networks. The main routing challenges for UAV networks are frequent link failures, packet losses, limited bandwidth, high routing overhead, triggered routing table updates, and low convergence rate in networks.

In this section, the challenging research issue that is the robustness and efficiency of routing in UAV networks is addressed. Five challenging issues are summarized here. It is hoped that researchers in the field will be interested in UAVs as a promising future technology.

A. LINK DISCONNECTION

Generally, UAVs are deployed in low densities and need to move with high mobility. Hence, the network topology changes frequently, and the communication nodes are frequently disconnected. This destabilizes the communication network, therefore having an undesirable impact on the efficiency of routing, as well as its performance. Broken connectivity in the network makes routing more complex than it already is in UAV networks. Owing to this complexity, designing routing protocols becomes a very challenging task. Thus, dynamic changes in the network negatively affect the routing performance and incur packet losses.

B. HYBRID METRICS

Most of the routing protocols are bound to issues related to delay and overhead. There are many possible metrics to consider for routing. To design efficient routing protocols, additional metrics, such as route mobility, QoS metrics, stability, link quality, and security metrics may be considered.

C. PERFORMANCE AWARENESS

In UAV networks, efficient data exchange between UAVs is difficult, and the network properties are quite different from MANETs and VANETs. One of the major drawbacks is that the simulation results of UAVs at high-speed motions show

TABLE 6. Comparison of position-based routing protocols for UAV networks.

Protocol	Location service	GPS	Path discovery	Single path	Multi path	Evaluation metrics*	Mobility model**	Latency	Simulation tools	Types of network
Single-path heterogeneous routing										
UVAR	☑	☑	NO	YES	NO	P, H, D	MM	High	NS-2	FANET-VANET
CRUV	☑	☑	NO	YES	NO	P, D, H	MM	High	NS-2	FANET-VANET
UAV-VN	☑	☑	NO	YES	NO	D	R	Low	-	FANET-VANET
UAVRT-MANET	☑	☒	NO	NO	YES	P, D	RPGM	Medium	NS-2	FANET-MANET
Single-path DTN routing										
P-OLSR	☑	☑	NO	YES	NO	P, D	C	High	Testbed	FANET
PR-DUAV	☑	☒	NO	NO	YES	D	RM	Low	-	UAV networks
LAROD	☑	☑	NO	YES	NO	P, O	PR	-	NS-2	FANET
DTS-TSP-D	☑	☒	NO	NO	YES	P, D	Ferrying	Low	MATLAB	UAV networks
AERORP	☑	☑	NO	YES	NO	P, D, O	-	High	NS-3	FANET
GRAA	☑	☑	NO	YES	NO	P, D	RWP	-	QualNet	FANET
Single-path non-DTN routing										
GPSR-ABPP	☑	☒	NO	YES	NO	P, O, D	RWP	Medium	NS-3	FANET
i-OLSR	☑	☑	NO	YES	NO	P, T, D	PM	Low	NS-3	FANET
ADRP	☒	☒	YES	YES	NO	P, D, O	RM	Medium	NS-2	FANET
GLSR	☑	☑	NO	YES	NO	P, D, T	RM	-	OMNET++	FANET
MPGR	☑	☑	NO	YES	NO	P, D, O	GM	Low	NS-2	FANET
GPMOR	☑	☑	NO	YES	NO	P, D, H	GS	Low	NS-2	FANET
OLSR_PMD	☑	☑	YES	NO	YES	P, D	-	Medium	NS-3	UAV networks
DSGR	☑	☑	NO	YES	NO	P, D	M	Low	-	UAV networks
RRPR	☑	☑	NO	YES	NO	H, R	RWP	-	Monte carlo	FANET
TARCS	☑	☑	NO	YES	NO	P, D, J	RWP+RPGM		NS-3	FANET
Multi-path non-DTN routing										
ARPAM	☒	☑	YES	NO	YES	P, T, L	-	-	OPNET	FANET
RGR	☑	☑	YES	NO	YES	P, D, O	RWP	Low	-	FANET
MUDOR	☑	☑	YES	NO	YES	P	RM	-	JAVA	FANET
GLMHRP	☑	☑	NO	NO	YES	P, D, O	RWP	Medium	-	FANET
Multi-path heterogeneous routing										
PASER	☒	☑	YES	NO	YES	P, D	C	Medium	OMNET++	FANET
Multi-path DTN routing										
LADTR	☑	☑	YES	NO	YES	P, D, O	GM	Low	NS-3	UAV networks

Evaluation metrics**: P: Packet delivery ratio, D: End-to-end delay, O: Overhead, H: Average number of hops, T: Throughput, J: Jitter, R: Route setup time
Mobility model**: C: Customized, GM: Gauss–Markov, RWP: Random waypoint, RM: Random movements, PR: Pheromone repel, MM: Manhattan model, M: Modified model, PM: Pursue mobility model, R: Realistic mobility, RPGM: Reference point group mobility (RPGM)

additional delay. Delay threshold is considered a challenging issue. With reactive routing protocols, excess overhead results from their use of an extra flooding process. Furthermore, minimizing the overheads for reactive-based and beacon-based protocols as well as minimizing packet losses from obstacles in the network are major challenges. For avoiding collision between multiple UAVs, collaboration and coordination among UAVs are essential.

D. EVALUATION TOOLS

A good number of simulation tools are used for routing protocol simulations of UAV networks and FANETs [132]–[134]. The majority of them do not show realistic or reasonable results. OPNET, NS-2, NS-3, and OMNET++ are the most used tools for performance measurement and evaluation of UAV routing protocols. These, however, do not support 3D communication and do not simulate any specified channels for communication between UAVs. Most simulators only support random mobility models, not predefined control-based mobility. According to review papers, most of the researchers use personalized simulators that do not support reuse of the code. Therefore, a new simulator tool that supports more realistic mobility models and predefined mobility to obtain more reasonable and realistic outputs is needed to design protocols for UAV networks.

E. SECURITY

Security is yet another concern for UAV routing protocols. Network layers are called the building blocks of a network, so future security concerns need be considered when design routing protocols, as UAVs are capable of hijacking, being used as weapons, or causing other damage. An authentication node may use to protect the UAVs from internal or external attacks. Additional security methods may be applied to make the routing protocol more secure. However, only a few routing protocols support security features [83].

TABLE 7. Comparison of routing protocols for UAV networks in field experiment.

Protocol	Experiment setup						Routing performance			
	Field test area	MAC protocol	UAV model	Speed of UAV	Transmission range	Altitudes	Mobility Model	Route Metrix	Evaluation metrics*	Hop count
DTN-GEO	400 m × 400 m	IEEE 802.15.4 IEEE 802.11n	Quadcopter	4.5 m/s	200 m	100 m	Real mobility	Shortest and best path	P, D, H	Multihop
EE-Hello	600 m × 600 m	IEEE 802.11b	-	5-50 m/s	150 m	150 m	GM 3D	Shortest path	P, D, O	Single hop
UAV-DM	800 m × 800 m	Ubiquiti rocket M5	X8 UAV	-	400 m	200 m	Real mobility	The best path	T, D	Multihop
MUAV-AD HOC	-	IEEE 802.11	Four-rotor UAV	-	30 m	50 m	Real mobility	Best path	D, P	Multihop
SIIAFC	100 m × 100 m	IEEE 802.11	DJI M100	2-5 m/s	20 m	80 m	Real mobility	Shortest path	E	Multihop
MUAV-R	900 m × 1600 m	IEEE 802.11	Fixed-wing UAV	-	115 m	120 m	Real mobility	-	RST	Single hop

Evaluation metrics**: P: Packet delivery ratio, D: End-to-end delay, O: Overhead, H: Average number of hops, T: Throughput, E: Energy consumption, RST: Route setup time
Mobility model**: GM: Gauss–Markov

TABLE 8. Summary of possible research directions.

Issue	Research directions	Recommended references
Link disconnection	New routing protocols can be designed by taking this issue into account in an effective way. Various localization techniques can also be used for the position estimation of high-speed UAV nodes.	Ref [95] , [99] , [109] , [117], and [124]
Hybrid metrics	Hybrid metrics can be used for designing energy-efficient and high-performance routing protocols and clustering algorithms.	Ref [122], [123], and [124]
Performance awareness	Fault tolerance can be considered to design a routing protocol. Performance awareness can be effectively exploited to develop a self-organizing network to avoid collision between UAVs.	Ref [91], [121], and [124]
Evaluation tools	Popular simulators such as MATLAB and NS-3 are being widely used for UAV networks.	Ref [132]–[134] and [137]–[139]
Security	The secure routing techniques including the jamming-resilient routing should be extensively addressed for trusted UAV communications.	Ref [116] and [118]

Further study is needed in network layering in UAV networks to ensure security, and prevent network attacks, likes spoofing, and denial of service (DoS). Compared to traditional public key-based system encryption, hashing techniques are more suitable and more secure. Traditional public keys cause network overhead and additional delay at the time of encryption of the message to be sent in a communication network.

Table 8 provides the possible research directions with suggested solutions for the five issues. The recommended references are also cited in the table for further investigation of interesting readers.

VIII. CONCLUSION

In this paper, several existing routing protocols for UAV networks have been surveyed in detail. Various design considerations, network architectures, and communication protocols for UAV networks have been introduced. Routing protocols have been classified into topology-based routing, position-based routing, hierarchical routing, deterministic routing, stochastic routing, and social network-based routing. Then, we analyzed the routing protocols in terms of various routing techniques, routing evaluation metrics, advantages and disadvantages of the routing protocols to compare the existing routing protocols in terms of key parameters and metrics. Finally, open issues and future challenges have been discussed. To the best of our knowledge, this is the first article where all categories of routing protocols are discussed. The results of our review show that all routing protocols for UAV networks must be considered with a low density of nodes and high mobility.

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