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A Survey on Cluster-Based Routing Protocols for Unmanned Aerial Vehicle Networks

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ABSTRACT In recent years, unmanned aerial vehicles (UAVs) have gained popularity for various applications and services in both the military and civilian domains. Multiple UAVs can carry out complex tasks efficiently when they are organized as an ad hoc network, where wireless communication is essential for cooperation and collaboration between UAVs and the ground station. Due to rapid mobility and highly dynamic topology, designing a routing protocol for UAV networks is a challenging task. As the number of UAVs increases, a hierarchical routing called clustering is necessarily required to provide scalability because clustering schemes ensure the basic level of system performance such as throughput, end-to-end delay, and energy efficiency. For approximately a half-decade, several survey articles have been reported on topology-based routing and position-based routing for UAV networks. To the best of the authors' knowledge, however, there is no survey on cluster-based routing in the literature. In this paper, cluster-based routing protocols for UAV networks are extensively surveyed and qualitatively compared in terms of outstanding features, characteristics, competitive advantages, and limitations. Furthermore, open research issues and challenges on cluster-based routing are discussed.

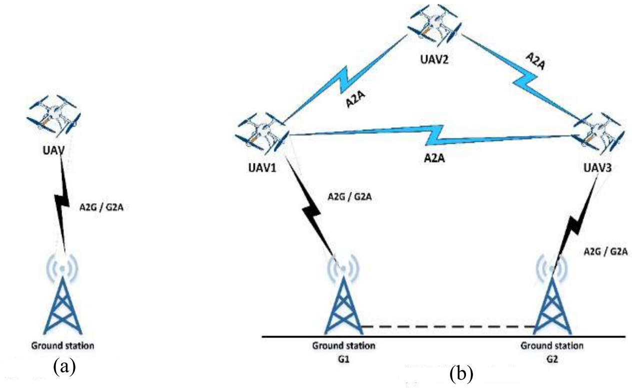
INDEX TERMS Unmanned aerial vehicle, drone, unmanned aerial vehicle network, flying ad hoc network, routing protocol, clustering algorithm, scalability.

I. INTRODUCTION

The rapid deployment of technologies such as low-cost Wi-Fi radio interfaces, sensors, global positioning system (GPS), and embedded microcomputers enables unmanned aerial vehicles (UAVs) to be extensively used in various application areas for military and civilian domains. Currently, UAV devices are popularly used in military and civilian applications. Some good examples are public protection and disaster relief operations [1], surveillance and reconnaissance [2], border supervision [3], autonomous tracking [4], managing wildfire [5], search and destroy operation [6], public safety [7], homeland security [8], wind estimation [9], remote sensing [10], traffic monitoring [11], and relay for ad hoc networks [12]. In addition to military and public domains, there are also so many commercial applications such as filmmaking [13], farming [14], Internet delivery [15], goods transportation [16], and architecture surveillance [17]. For example, Nokia has recently developed an ultra mini 4G base station weighing only 2 kg, which was successfully mounted on a commercial quad-copter to provide coverage over a remote area in Scotland [18]. Moreover, Amazon designed a drone called Amazon Prime Air [19] to safely deliver packages to customers within half an hour by using a small drone.

Deploying a large number of drones would bring some challenges such as ensuring collision-free and seamless operation of drones. UAVs can be categorized into four types based on their cruise duration and action radius: high-range UAVs operating at high altitudes and long duration, medium-range UAVs having an action radius of 700 to 1000 km, low-cost and short-range small UAVs having an action radius of less than 350 km and flight span of approximately less than 3 km, and finally, mini drones having limited cruising speeds of 10 to 30 km/h, cruising duration of less than 1 h, and weights of less than 1 kg.

For cooperation and collaboration between multiple UAVs, inter-UAV wireless communication is essentially required to form a UAV network or flying ad hoc network (FANET). UAVs are also called drones, and the three terminologies, namely, UAV network, FANET, and drone ad hoc network are interchangeably used. There are two types of UAV networks as shown in Figure 1. In a single-UAV network, a UAV is



(a)
(b)

FIGURE 1. Single- and multi-UAV networks.

linked to a ground station or a satellite. In a multi-UAV network, multiple UAVs are connected to each other as well as to a ground station or a satellite. UAVs in multi-UAV networks can be dynamically configured in different topologies from time to time. In general, there are four types of communications in multi-UAV networks: air-to-ground (A2G) (downlinks), ground-to-air (G2A) (uplinks), air-to-air (A2A) (inter-UAV links), and ground-to-ground (G2G). A2G communication links transmit data such as images or videos from air to ground. G2A communication usually transmits the control signal from a ground station to UAVs. In a multi-UAV network, UAVs can operate in an ad hoc fashion, where UAVs need to communicate among themselves to make consensus decisions and perform data exchanges through A2A communication links. G2G links provide the communication between multi-ground stations.

For transmission between UAV nodes, a routing protocol is necessarily required. The topology of UAV networks is highly dynamic because of the dynamic three-dimensional (3D) environment with varying UAV speeds. UAV links may be frequently disconnected. Another challenge is range restriction between UAVs and the ground station. As the number of UAVs increases, a hierarchical routing called clustering is essentially required to provide scalability because clustering schemes ensure the basic level of system performance such as throughput, end-to-end delay, and energy efficiency. In such a clustered configuration, only the elected cluster head (CH) will be responsible for communication with the ground station. Due to high mobility, dynamic topology, and uneven UAV distributions, the development of a routing protocol ensuring reliable communication is very tough and challenging in UAV networks [20].

In some scenarios, UAV networks can be viewed as a unique form of mobile ad hoc networks (MANETs) and vehicular ad hoc networks (VANETs). Recently, several research works have been solely devoted to applying existing ground networks such as VANETs to UAV networks [21]. However, the rapid mobility and highly dynamic topology in UAV networks make the adaptation difficult, limiting the network performance and reliability. Some approaches and contributions have been proposed, particularly those based on clustering approaches during the last several years. Some cluster-based routing protocols have been proposed for UAV-aided data gathering, data replying, and data forwarding in wireless sensor networks (WSNs). These types of routing protocols have been designed based on frequent disconnection between UAV nodes.

UAV networks need highly accurate localization of data with smaller time intervals because of the high speed and different mobility patterns in a multi-UAV environment. However, GPS provides position information at one-second interval, and it may not be adequate for UAV network protocols. Therefore, an inertial measurement unit (IMU) that can be calibrated by the GPS signal and can provide the position of the UAV at a faster rate was introduced [22]. For range corrections with an accuracy of approximately 10 m, some researchers proposed the differential GPS or assisted GPS by using ground-based reference techniques [23], [24]. The received signal strength indication (RSSI)-aided cluster-based routing protocol was also reported [25].

Recently, some comprehensive survey works on topology-based routing and position-based routing for UAV networks have been reported [26]–[32] as summarized in Table 1. To the best of the authors' knowledge, however, there is no survey on cluster-based routing in the literature.

TABLE 1. Summary of existing survey articles on routing protocols for UAV networks.

Survey Article	Summary of survey articles
Ref. [26]	Surveys topology-based routing protocols including static, proactive, reactive, and hybrid routing, but no comparative study on routing protocols
Ref. [27]	Surveys topology-based routing and MANET topology-based routing and introduces seamless handover and energy efficiency
Ref. [28]	Introduces a comprehensive survey on position-based routing protocols for FANETs with their various categories
Ref. [29]	Surveys topology-based routing and position-based routing including static, proactive, reactive, hybrid, and geographical routing protocols, but no comparative study on those routing protocols
Ref. [30]	Surveys single-hop and multi-hop topology-based routing protocols such as static, proactive, reactive, hybrid, and position-based. A comparative study of existing routing protocols is given.
Ref. [31]	Surveys single-path and multi-path position-based routing protocols including forwarding strategy such as deterministic progress-based, randomized progress-based, face-based, hybrid, restricted directional flooding, randomized directional flooding, and classic flooding. A comparative study of those routing protocols is given.
Ref. [32]	Surveys four clustering algorithms based on weighted clustering metrics for UAV networks

In this study, cluster-based routing protocols for UAV networks are extensively surveyed and qualitatively compared in terms of outstanding features, characteristics, competitive advantages, and limitations. The main contributions of this study are as follows:

- A comprehensive and state-of-the-art survey on cluster-based routing protocols for UAV networks is provided.

To the best of the authors' knowledge, this is the first attempt to review and compare the cluster-based routing protocols extensively.

- The cluster-based routing protocols for UAV networks are systematically classified according to the underlying clustering mechanism. Existing 18 cluster-based routing protocols are categorized.
- The surveyed cluster-based routing protocols are qualitatively compared with each other in terms of outstanding features, characteristics, competitive advantages, and limitations. This comparison may help researchers and engineers to choose the most appropriate cluster-based routing protocol based on their requirements.
- Important open research issues and challenges in designing a cluster-based routing protocol for UAV networks are also summarized and discussed.

The rest of this paper is organized as follows: In the next section, the design issues on UAV routing protocols are summarized. In Section III, the cluster-based routing protocols for UAV networks are extensively reviewed with regard to their key features, distinguishing characteristics, potential advantages, and limitations. In Section IV, the reviewed routing protocols are qualitatively compared in terms of outstanding features, characteristics, competitive advantages, and limitations. In Section V, open research issues and challenges on cluster-based routing in UAV networks are discussed issue by issue. Finally, this paper is concluded in Section VI.

II. DESIGN ISSUES OF UAV ROUTING PROTOCOLS

In this section, the important design issues of UAV routing protocols, namely dynamic topology, network formation, high mobility, low latency, and variable communication links, are summarized. Each design issue is discussed briefly.

A. DYNAMIC TOPOLOGY

Peer-to-peer connections are formed among UAVs to maintain coordination and collaboration, and they can be effectively achieved via clustering [33]. For homogeneous 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 CH of each cluster is responsible for downlink communication and inter-cluster communication. In the process of clustering, after forming the dynamic clusters, the UAVs are relocated at the positions vertically projected on the centroids of clusters as shown in Figure 2. Each UAV serves a cluster of mobile devices, and mobile devices and UAVs can be denoted as $\{x_v^m, y_v^m, 0$ and $\left\{x_n^u, y_n^u, z\right\}$, respectively. Therefore, the new position of each UAV is vertically projected on the corresponding centroid of a new cluster as the UAV moves.

B. NETWORK FORMATION

Network formation is tightly coupled with the formation of UAVs in multi-UAV networks. To manage a large number of UAV nodes and several static ground stations is one of the significant challenges. An extensive set of mini-UAVs can be present as a set of intelligent swarms. Self-organized UAV formation is an example of an intelligent cluster formation. In intelligent clustering, UAVs are able to adapt to dynamic connectivity change. After a disruption in connection, UAVs may self-organize to reconnect themselves.

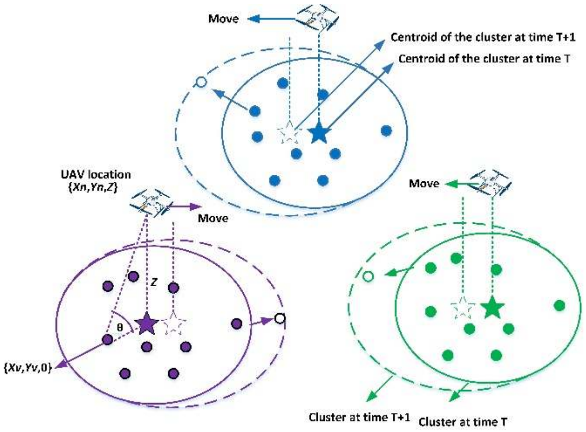


FIGURE 2. Dynamic UAV clustering.

C. HIGH MOBILITY

In UAV networks, mobility models are application-dependent. The mobility of UAV nodes is higher than that of VANETs and MANETs [34]. All UAV nodes are highly mobile, with speeds ranging from 30 to 460 km/h [35]. In the case of some multi-UAV systems, global path plans are preferred for UAVs. However, multi-UAV systems work autonomously, where the path is not predefined. Mobility models also depend on the type of UAVs considered. UAVs are categorized as large UAVs, small UAVs, and mini UAVs [36]. For patrolling applications, where UAVs can adopt flexible trajectories, other models such as random waypoint mobility model can be used [37], [38]. In the Gauss–Markov mobility model [39], the movement of UAVs depends on previous speed and directions that assist UAVs in relaying networks [40]. Node mobility is a significant issue in UAV routing.

D. LOW LATENCY

Disaster monitoring, surveillance, and search and rescue operations require minimal latency as the information needs to be transmitted at very high speeds. The concept of priority schemes may be used in UAV networks to control and minimize latency [41]. In addition, priority-based routing protocols can be used to manage the quality of service (QoS) for various message types. Therefore, choosing the most suitable routing protocol is essential for controlling the latency and improving the QoS of UAV networks. A satisfactory control of collision and congestion plays a vital role in reducing latency as well.

E. VARIABLE COMMUNICATION LINKS

Currently, most public and civilian applications can be performed using multi-UAV networks. In multi-UAV systems, the network may have different types of communication links such as UAV-to-UAV and UAV-to-ground links. The key features of multi-UAV networks are reliability and survivability through redundancy. Failure of a single UAV causes the network to reorganize and maintain communication by using other nodes.

F. BASE COMMUNICATION TECHNOLOGY

In UAV networks, the IEEE 802.11 standard technology is widely used. For less bandwidth requirements, the IEEE 802.14.4 standard can be effectively used for UAV-to-UAV communications. The IEEE 802.14.4 enables a low power and less complicated implementation with lower data rate. The IEEE 802.11 can be used 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 medium access control layer should address a few challenges, such as packet delays, optimal channel utilization, high mobility, and variable link quality. In UAV networks, link quality fluctuations occur due to varying distances between nodes and high mobility. In order to avoid restrictions on the transmission range, UAVs can communicate with each other using an ad hoc fashion. This wireless network is used to transmit data between nodes in multi-hop communications for various applications. In cluster-based UAV networks, not all UAVs can communicate with the ground station or satellites: only CHs can communicate with ground stations.

III. CLUSTER-BASED ROUTING PROTOCOLS FOR UAV NETWORKS

In this section, cluster-based routing protocols for UAV networks are extensively surveyed with regard to their key features, distinguishing characteristics, potential advantages, and limitations. Because clustering provides many benefits such as scalability, reliability, fault tolerance, data aggregation, energy efficiency, coverage, connectivity, and reduced delay, the cluster-based routing protocols will be developed and used more popularly in the future as the number of UAVs is increased in UAV networks. The existing cluster-based routing protocols for UAV networks can be classified as shown in Figure 3. The 18 cluster-based routing protocols shown in Figure 3 are extensively reviewed in this section. First, the routing protocols based on probabilistic clustering are surveyed, and then those based on deterministic clustering are investigated. The operational behavior, inherent characteristics, competitive advantages, limitations, and application areas of the protocols are addressed.

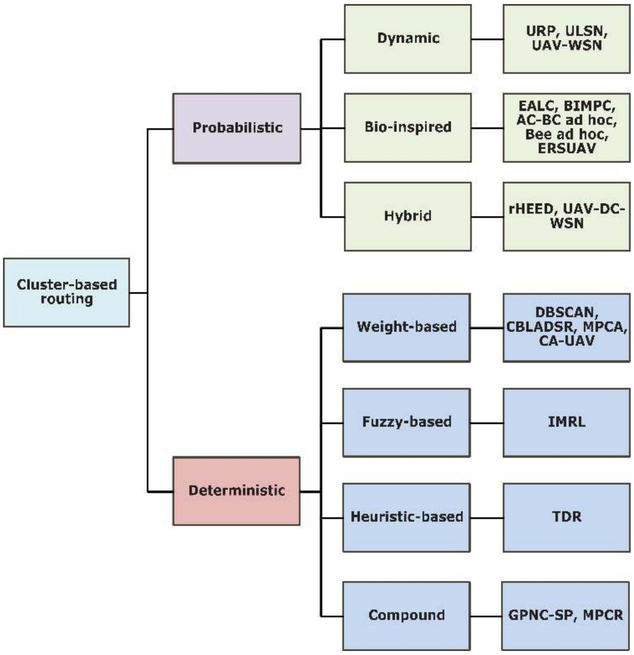


FIGURE 3. Classification of cluster-based routing protocols for UAV networks.

A. CLUSTER-BASED ROUTING PROTOCOLS BASED ON PROBABILISTIC CLUSTERING

The major objective of the probabilistic cluster-based routing is to make the network lifetime longer. In some of the probabilistic cluster-based routing protocols, the CH is randomly elected. In this section, the probabilistic cluster-based routing protocols are investigated in detail.

1) UAV ROUTING PROTOCOL (URP)

Uddin *et al.* [42] presented a UAV-assisted dynamic clustering named URP for crop health monitoring. URP is a dynamic cluster-based routing protocol that aims to collect data from a selected area. In their study, a UAV-based mobile sink node collects data from scattered nodes based on a random walk or predefined path. A UAV sends a beacon message to activate all sensor nodes residing in its neighbors, and it makes a cluster by considering path and data type.

In URP, the tasks of cluster formation and CH election are conducted dynamically. Every node participates in the CH election process based on its probability calculated by using a Bayesian classifier. The dynamic clustering scheme in URP is shown in Figure 4. The routing cluster nodes are grouped into three types, namely cluster members (CMs), candidate clusters (CCs), and candidate CHs (CCHs). CCHs and UAV participate in the CH election process to nominate a node as a CH. A Bayesian classifier [43] is used to calculate the CH election process.

- Advantages: URP can be effectively used in a quickly deployed UAV network without any existing infrastructure. Network lifetime is significantly improved owing to the use of dynamic clustering.

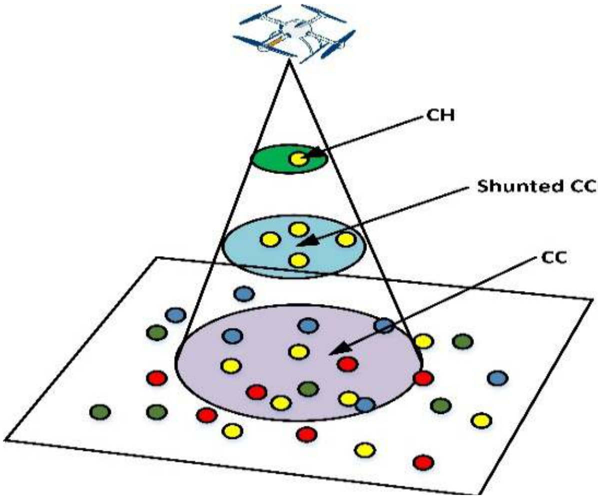


FIGURE 4. Dynamic clustering scheme in URP.

- Limitations: URP is designed only for WSNs assisted with a single UAV for crop health monitoring.
- Potential application: URP can be used for the UAV-based Internet of things (IoT) technology for agriculture to take care of crop health.
- Possible future improvements: Future improvements of URP may be possible in many ways. Instead of a single UAV, multiple UAVs can be used in a coordinated way. A single-hop transmission in URP can be extended to a multi-hop transmission scheme.

2) UAV-BASED LINEAR SENSOR ROUTING PROTOCOL (ULSN)

Jawhar *et al.* [44] presented a cluster-based linear-sensor routing protocol called ULSN. ULSN aims to reduce the energy consumption used in data transmission and extend the network lifetime. In ULSN, four types of nodes are used: sensor nodes (SNs), relay nodes (RNs), a single UAV, and sinks. SN uses a multi-hop communication to transmit data to the nearest RN. RN acts as a CH to its surrounding RNs. During the process, the UAV node moves back and forth along and collects data from the RNs.

The UAV contains GPS information, which is used for synchronization and localization of RNs and SNs. The UAV moves to RNs with a constant speed in the forward direction, and it forwards the data to the secondary sink in the opposite direction. At constant speed, the maximum and average message delays of the UAV are calculated as

$$T_{max}^{CSU} = \frac{(n+1)\,d}{s}$$

and

$$T_{avg}^{CSU} = \frac{(n+1)\,d}{2s}, \tag{1}$$

where n is the number of RNs, d is the distance between two RNs, s is the speed of UAV, and CSU is the constant speed of UAV. For the maximum delay, a message in the UAV must traverse the entire segment to go to the target sink. Minimum delay occurs when the message is collected from the last node just before the UAV arrives at the target node.

When UAV is in the range of RN, RN is able to exchange data before the UAV leaves the area. The height of the UAV from the ground, h, for data exchange between UAV and RN is expressed as

$$h = 2R_c \sin\left(\frac{\pi}{2} - \alpha\right) = 2R_c \cos(\alpha), \tag{2}$$

where R_c is the communication range of an RN, and α is the angle between the vertical line and intersection point of the communication point of the communication range circle of RN. When the UAV comes within the RN communication range, it inquires the current buffer size of the RN by transmitting a control message to the RN. The UAV makes the decision based on the allocated delay quota of the RN. If allocation delay is good enough to download all data, the UAV sets the speed in such way that helps to download all data. If the delay quota is less than or equal to the delay required in downloading the entire bugger, then the UAV speed is set as the in-range distance (d) divided by the delay quote of RN node.

- Advantages: ULSN can effectively reduce the resource requirements such as buffering memory, processing, end-to-end data delivery delay, reliability, and fault tolerance. If one segment fails due to failure of SN, RN, UAV, or sink, other segments of the network would work well.
- Limitations: ULSN routing is designed only for data collection in WSNs with a single UAV. High end-to-end delay may occur because the UAV moves slowly outside of the communication zone of sensors.
- Potential application: The ULSN framework can be used to collect data and transmit from sensors to the sink node.
- Possible future improvements: It may be possible to expand the other types of sensor networks. Future work can be focused on the use of multiple UAVs per segment and provide efficient algorithms for optimal UAV routes.

3) UAV-WIRELESS SENSOR ROUTING PROTOCOL (UAV-WSN)

Martinez-de Dios *et al.* [45] presented a cluster-based routing protocol called UAV-WSN. UAV-WSN contains two main cooperative behaviors: operational results of WSN are used to update the UAV flight plan, and the UAV routing path depends on the WSN operation to improve the data location performance. The authors used a dynamic cooperation of WSN and UAV for data collection. The UAV-WSN routing protocol aims to achieve a better performance in the network lifetime and energy efficiency compared to non-cooperative UAV-aided WSN routing. In UAV-WSN, WSN nodes are formed in clusters using a distributed cluster algorithm.

The UAV-WSN routing scheme is shown in Figure 5. There are two types of nodes: CH and CM. CM gathers sensor

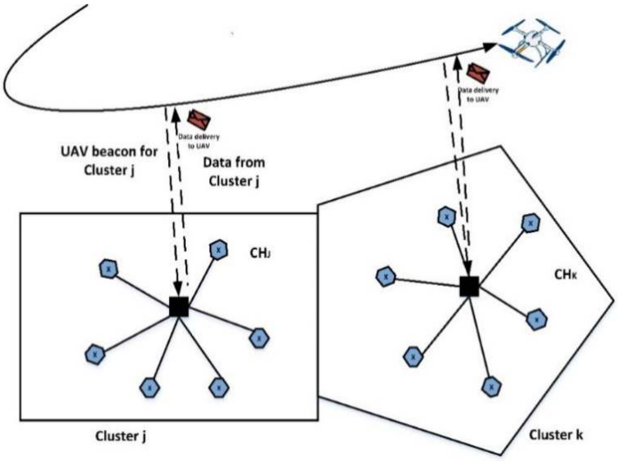


FIGURE 5. Cluster-based UAV data collection.

readings and periodically transmits them to the CH. After receiving the beacon from the single UAV, CH sends the data. All CM nodes monitor the activity of the CH. After a certain period, if node *i* does not detect any activity from its CH, then it proposes itself as a CH. For data collection, the location of CHs defines zones. The UAV makes a flight plan based on the zonal information. The allocation of WSN collection zones for UAV is calculated as

$$(i, n) = \arg min_{(j.m)} \left\{ c_{it} \left(UAV_m, WZ_j \right) + C_{it} \left(UAV_m \right) \right\}, \quad (3)$$

where *i, j, m*, and *n* represent the UAV zones, WZ_j is the allocation for UAV_m, $C_{it}\,(UAV_m)$ represents the cost of the path of UAV_m, which is computed as the sum of the Euclidean distance between the centers of WSN collection zones allocated for UAV_m, and $c_{it}\left(UAV_m, WZ_j\right)$ represents the Euclidean distance between the centers of WZ_j and previous WSN data collection zone allocated for UAV_m. For the new CH, it sends information to the central station about the CH rotation.

- Advantages: In UAV-WSN routing, both CH and non-CH nodes sleep during the inactive periods. All nodes use a wake-up radio receiver. For the CH rotation, the UAV-WSN routing finds a better candidate to elect as the next CH.
- Limitations: UAV-WSN is designed only for the single-hop cluster-based routing. It is not suitable for collecting data in large WSNs.
- Potential application: UAV-WSN routing can be used to collect data from sensor nodes.
- Possible future improvements: For the future improvement of UAV-WSN, it may be possible to expand the multi-hop cluster. Multi-hop clusters can reduce the number of clusters and simplify UAV routing at the expense of increasing the node energy consumption.

4) ENERGY-AWARE LINK-BASED CLUSTERING (EALC)

Aadil *et al.* [46] presented the EALC routing protocol for FANET. This routing protocol aims to address two major problems in UAV routings such as short flight time and inefficient routing. To resolve both problems, the authors used K-means density clustering. An optimal cluster enhances the cluster lifetime and reduces the routing overhead. In the process of CHs election, EALC uses a variant of the K-means density algorithm. The conventional K-means density algorithm uses one parameter for degree of neighborhood, but EALC uses two parameters, namely energy level and distance to the neighbors for the election of an optimal CH. EALC aims to enhance the cluster lifetime, improves the energy consumption, and saves the node energy by efficiently selecting the transmission power of nodes. EALC employs a combination of two bio-inspired algorithms, the ant colony optimization (ACO) and gray wolf optimization-based clustering schemes for cluster building time, cluster lifetime, and energy consumption.

In EALC, nodes are grouped into a cluster using K-means shorted fitness algorithm and make communication through the CHs. UAV nodes periodically broadcast the energy level and position of CHs. If the CH fitness falls below the threshold level of 20%, then all nodes of that cluster may be considered as unclustered nodes. When 20% of all nodes are unclustered, then a new CH may be called. After obtaining the position information and transmission range, every node calculates its fitness value and transmits it to neighboring nodes. The fitness value is calculated using the following equation:

$$Fitness = \frac{w1 \times Energy_{Res}}{(w2 \times avg_{dis})\,(w3 \times delta_{diff})}, \quad (4)$$

where $Energy_{Res}$ is the node residual energy level, avg_{dis} represents the average distance to the neighboring nodes, and $delta_{diff}$ is the delta difference. For calculating the delta difference load balancing factors, $w1$, $w2$, and $w3$ are weight metrics for energy, average distance, and delta difference, respectively. Delta difference is the deviation of node degree of the neighborhood from the ideal degree.

Most of the previous works are based on statically assigning the weight to fitness parameters, but static weight assignment may be biased on the fitness function and not able to provide accurate results. If all nodes are in the transmission range of each other, one node needs to be elected as a CH based on its fitness value. In EALC, the energy level of the nodes is considered as a fitness value. If node *A* has an energy level of 90% whereas the remaining nodes have an energy level of approximately 50%, such a difference makes node *A* as a CH. Another condition is that if node *F* has an energy level of 30% while the others have 50% but node F has a shorter distance compared to the other nodes, node *F* may be the elected as a CH.

- Advantages: In EALC, the election of CH is not based on one static weight calculation; it requires energy and transmission range to obtain the proper CH. A long CH makes the network more stable and increases the network lifetime. EALC optimizes the routing calculation and saves UAV energy by controlling the transmission range and efficiently clustering the network.

- Limitations: The EALC routing protocol only considers UAV nodes with moderate mobility.
- Potential application: EALC can be used for peer-to-peer UAV communications.
- Possible future improvements: It may possible to perform efficient routing with very high mobility nodes in the future.

5) BIO-INSPIRED MOBILITY PREDICTION CLUSTERING (BIMPC)

Yu *et al.* [47] presented the BIMPC protocol for ad hoc UAV networks. BIMPC aims to address the high mobility issue and quick network topology change in UAV networks. The BIMPC routing protocol combines the mobility character of UAV and transplants the foraging model of Physarum polycephalum to the field of ad hoc networks.

BIMPC includes the cluster formation and cluster maintenance. It is assumed that the current UAV may calculate the sum of the value of one-hop neighbors and stability of the established cluster; not all one-hop neighbor UAVs are not in the communication range of the current UAV. To become a CH, all UAV nodes need to calculate the value of neighboring nodes. The calculation process is as follows:

$$CHP_i(t) = \sum_{j \in N} \frac{d}{dt} \Delta P_{ij}(t), \tag{5}$$

where i and j are UAV nodes, ΔP_{ij} denotes the flux through the pitot tube, $CHP_i(t)$ represents the probability of the current UAV i to become a CH, and N is the set of one-hop neighboring UAVs of the current UAV node i. In the process of cluster formation, all UAVs broadcast the *Hello* packets to their neighbors and make a neighbor list. When the current UAV receives two successive *Hello* messages from its neighboring UAVs, then, the current UAV calculates the link subsistence probability and movement of the current and neighboring UAVs.

When a UAV receives a $CHP_j(t)$ message from its neighbors, it compares with its own $CHP_i(t)$. If the $CHP_i(t)$ is larger than the other $CHP_j(t)$, the UAV node i continues to broadcast it to become the CH. However, if $CHP_i(t)$ is the less than other $CHP_j(t)$, UAV node i broadcasts the normal packet. If the UAV node i is not receiving the *Hello* packet for a long time, it may declare itself as a CH. The BIMPC algorithm can predict the breakage of links and any changes in the cluster. When the current cluster head CH_i decreases its $CHP_i(t)$ value drastically, it is not perfect to become a CH. Thus, the CH needs rotation, and the CH rotation formula is expressed as

$$ACHP_i(t) = \frac{1}{M} \sum_{j \in N} \frac{d}{dt} \Delta P_{ij}(t), \tag{6}$$

where i and j are the UAV nodes, N is the set of one-hop neighboring UAVs, and M represents the number of UAV nodes in the cluster.

After a time interval T, when the value of two $ACHP_i(t)$ is larger than $\emptyset$, it indicates that the current CH_i is no longer appropriate to become a CH. The rotation of CH depends on the following condition:

$$\Delta ACHP_i(nT) = ACHP_i(t - nT) - ACHP_i(t) > \emptyset, \tag{7}$$

where n is a positive integer, and T is the period of the *Hello* packets.

- Advantages: The BIMPC routing shows a better performance in cluster formation and maintenance of highly dynamic clustering in large-scale UAV networks. The BIMPC cluster structure is more stable and requires less overhead in routing.
- Limitations: The BIMPC routing protocol only considers UAV nodes with moderate mobility.
- Potential application: BIMPC routing can be used for highly dynamic large-scale ad hoc UAV networks.
- Possible future improvements: A future improvement of BIMPC is to consider UAV nodes at high speeds.

6) ANT COLONY-BEE COLONY AD HOC ROUTING (AC-BC AD HOC) AND BEE AD HOC ROUTING (BEE AD HOC)

Leonov [48], [49] presented a bio-inspired routing based on ant and bee colonies for FANET, which uses a probabilistic technique and meta-heuristic-based routing. The AC-BC ad hoc routing protocol aims to address the UAV common issues such as mobility, topology control, and movement in 3D space. The goal of the bee colony is to consider the source with the maximum nectar amount. For developing this behavior in the routing model, some methods have to be considered such as search space formation, formation of scout-agent swarm and forager-agent swarm, selection of the basic sites among the promising ones to explore the neighborhoods, and information transfer among the scouts and foragers. The principal operation of the bee colony algorithm is to find the promising sites and their neighborhoods in the search space.

In AC-BC ad hoc, the ACO is addressed as the modeling of ant behavior to find the shortest route from the anthill to the food source. It is assumed that at first iteration ($l = 1$), n_r scout agents spread randomly in the search space. The random generation in different sites is expressed as $R = \{r_s | s = 1, 2, \ldots n_r\}$, where r_s defines the basic site, s is the search space, and n_r is the initial number of the scout agents. The search for a problem solution is defined as $Z = \{z_k | k = 1, 2, \ldots l\}$, where each ant z_k constructs its own problem solution, and k is the number of specific problem solutions. At each stage of t, the agent applies a probabilistic rule for its next vertex. The probability of P_{ik} vertex is calculated as

$$P_{ik} = \frac{f_{ik}}{\sum_i f_{ik}}, \tag{8}$$

where i is the vertex number, and f_{ik} is measured, the parameters being the total level of the pheromone of the graph G edge connecting x_i to the vertex $e_k(t)$. Assume that $e_k(t)$ is the last vertex of $D_k(t)$. In the second stage, constructed

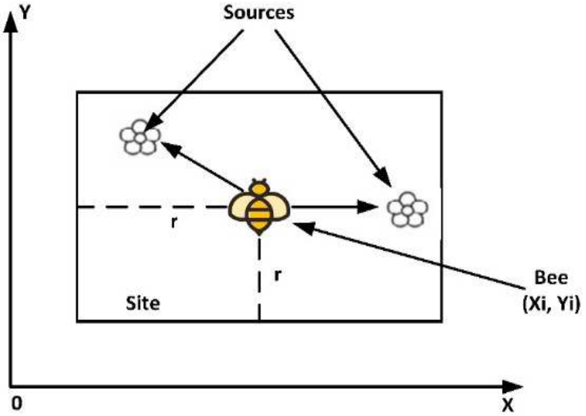


FIGURE 6. AC-based model for determining the site for nectar search.

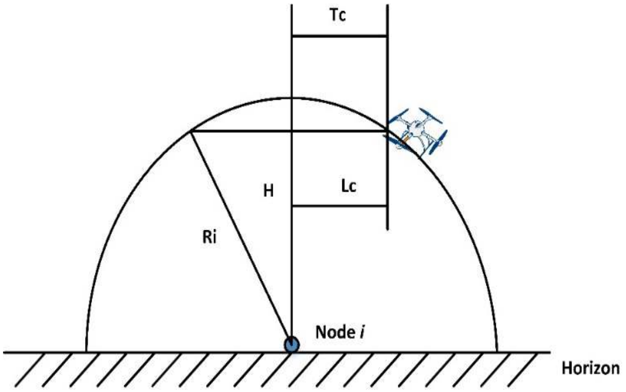


FIGURE 7. Delay calculation method from sensor node i to UAV.

route D_k is defined as

$$\Delta\tau_k(l) = \frac{Q}{F_k(l)}, \tag{9}$$

where Q is a constant, which is set to be the length of the shortest path estimated with a heuristic method, l is the iteration number, $\Delta\tau_k(l)$ is deposited by the ant Z_k on each edge to constructed route D_k, and $F_k(l)$ is the target function for the solution obtained by Z_k. The model for determining the site of nectar search is shown in Figure 6. The main difference between the ant and bee colony algorithms is that, in the ant colony (AC), intermediate nodes make no decision on routing, as all decisions come from the source node.

- Advantages: The AC-BC ad hoc routing protocol performs well in terms of end-to-end delay, throughput, and routing overhead compared with conventional routing protocols. It is a stable routing when the topology of UAV network changes.
- Limitations: In AC-BC ad hoc routing, the UAV may move randomly in the communication zone and take the sequences of a random decision and the probability distribution changes by iteration.
- Potential application: The AC-BC ad hoc is suitable for highly dynamic peer-to-peer UAV communication and traffic monitoring.
- Possible future improvements: In the future, implementation of a hybrid cluster-based routing may possible by a combination of ant and bee colony routing algorithms.

7) EFFICIENT ROUTING STRATEGY FOR UAVs (ERSUAV)

Yang *et al.* [50] proposed an AC-based probabilistic cluster routing algorithm called ERSUAV, which aims to achieve an efficient routing strategy for UAVs by integrating the features of clustering of WSNs and UAV devices on the same platform.

It is assumed that all nodes of the network are stationary, CHs are location-aware equipped with GPS, UAV knows the location information of all CHs, and the length of the transmitted data for each node is the same. The area is divided into a number of clusters, where the UAV flies above the CH to collect data. Delay calculation is shown in Figure 7. In the figure, H is the height between sensor nodes to the UAV position, and R_i is the communication range of node i for n visited number of nodes. In ERSUAV, the total delay of UAV is defined as

$$T_{all} = T_1 + \sum\nolimits_l^n (T_c + T_s + T_{ij}) + T_3 \quad \text{and } T_c = \frac{l_d}{V_c}, \tag{10}$$

where n is the number of visited nodes, l is the data packet, T_c is the delay of constructing communication between link i and j, T_s is defined as the delay of transmitting data between the node and UAV, T_{ij} is the delay of flight from node i to j, T_3 is the delay of flight of UAV from the last node to the data center, l_d denotes the length of data, and V_c is the bit per second. The energy consumption of UAV is defined as

$$P_{all} = P_1 + \sum\nolimits_l^n (P_c + P_s + P_{ij}) + P_3, \tag{11}$$

where P_1, P_c, P_3, P_{ij}, and P_s are the energy consumption of the flight of UAV from the data center to the CH, energy consumption from the link between i and UAV, energy consumption of UAV from the last node to the data center, energy consumption of flight node i to node j, and energy consumption between node and UAV, respectively.

The ultimate goal of ERSUAV is to minimize the delay and save energy. The delay and energy consumption depend on the distance among the nodes. For minimizing the delay and energy consumption, the authors proposed an ACO-based optimal path plan for UAV, in which the probability that ant k moves from node i to node j at time t is defined as

$$P_{ij}^k(t) = \begin{cases} \dfrac{\tau_{ij}^{\alpha}(t) \times \eta_{ij}^{\beta}(t)}{\sum_k \tau_{ij}^{\alpha}(t) \times \eta_{ij}^{\beta}(t)}, & \forall_{j \in N}, \quad \text{and } j \notin M^k, \\ 0, & \mathit{otherwise} \end{cases} \tag{12}$$

where α and β are the angles, M is the active sensor nodes in the cluster, $\eta_{ij}(t) = \frac{1}{d_{i,j}^2}$, N_i are the neighboring nodes of node i, and $\tau_{ij}(t)$ pheromone is updated by local and global means.

- Advantages: The ERSUAV routing protocol shows good scalability, less delay, and higher efficiency compared to conventional routings.
- Limitations: ERSUAV routing is designed based on a centralized-based clustering scheme. Centralized-based clustering has a limitation on network lifetime and it is not an optimized method for electing the CH.
- Potential application: ERSUAV is suitable for gathering data in farmland-based WSNs such as for monitoring temperature, humidity, soil moisture, and pH.
- Possible future improvements: In the future, ERSUAV may be extended to embedded platforms.

8) RSSI-BASED HYBRID AND ENERGY EFFICIENT DISTRIBUTED ROUTING (rHEED)

Okcu and Soyturk [51] presented a hybrid and energy efficient distributed clustering, which is an improvement of HEED. The algorithm aims to reduce the energy consumption in both the clustering phase and data-gathering phase. rHEED constructs more stable and well-balanced clusters to avoid the single CH problem. In rHEED, the authors proposed a UAV-aided WSN clustering method. Static sink node is not suitable due to its higher energy consumption and less reliability. The use of a UAV-based mobile sink node is an effective method of collecting data from sensors. In rHEED, the authors focused on RSSI-based clustering.

In their study, they pointed out the problem of UAV-based sink node such as some nodes within the network may remain uncovered due to UAV path and altitude. Sensor nodes are randomly deployed in the area, and sensor nodes are location-unaware. The HEED routing protocol has several limitations such as single CHs exist with no member; thus, owing to a single CM, the number of CH increases. The numbers of CHs significantly vary without any control, resulting in unequal cluster size and no information on the position of the sink node.

In rHEED, CHs are elected based on the residual energy level of nodes and position of the nodes near the UAV. rHEED solves the single CH problem. Uncovered nodes are connected to the CH through multi-hop paths after the CH election. rHEED has several features, e.g., clustering is completely distributed; after completing the clustering process, each node is either a CM or a CH, and positions of the CH node are nearest to the UAV. Sensor nodes record the RSSI values from UAV beacons and use these values in the clustering process. Nodes can record more than one RSSI value of the UAV; in this case, the peak value will be taken into consideration during the CH election. Otherwise, the node calculates the average RSSI value of UAV beacons.

At first, the node discovers its neighboring nodes by calculating the cost based on the $RSSI_{peak}$, which is exchanged between the neighboring nodes with the use of advertisement packets. The cost calculation formula is defined as

$$Cost_t = \max\left(RSSI_{i,\emptyset}\right), \tag{13}$$

where i denotes each sensor node, and $RSSI_{i,\emptyset}$ is the RSSI level for sensor node i obtained from UAV beacons during its connection time $\emptyset$. A sensor node that has a connection with UAV decides to become a CH by calculating the CH_{prob} in the following way:

$$CH_{prob} = \begin{cases} max\left(C_{prob} \times \dfrac{E_{residual}}{E_{max}}, P_{min}\right), & if\ Cost_i > 0 \\ 0, & if\ Cost_i = 0, \end{cases} \tag{14}$$

where C_{prob} denotes the probabilistic value that limits the initial CH announcements, P_{min} is a small value used to limit the iteration number, and E_{max} is the highest power level of the node. Nodes with higher residual energy $E_{residual}$ and having connectivity with the UAV may have a higher probability of becoming a CH.

- Advantages: The rHEED routing uses the RSSI value received from UAV and remaining energy levels of a sensor node for electing the CH. The rHEED routing protocol provides a more stable and well-balanced cluster.
- Limitations: The rHEED routing is designed only for a single-UAV-based WSN communication.
- Potential application: The rHEED routing protocol is suitable for transmitting aggregate data from the sensor node to a mobile sink node.
- Possible future improvements: The rHEED routing may be improved by using a multi-UAV-based concept in the future.

9) UAV-BASED DATA COMMUNICATION FOR WSNs (UAV-DC-WSN)

Jawhar *et al.* [52] proposed a cluster-based delay-tolerant UAV routing called UAV-DC-WSN. This routing aims to focus on the use of a UAV for data collection in large-cluster networks.

The UAV-based routing model avoids the multi-hop routing approach leading to significant energy savings, increased network lifetime, and added flexibility of node deployment. In UAV-DC-WSN, the authors proposed a store-and-forward model. In this routing model, the UAV moves over the sensor node area. Once the UAV is in the range of sensor RN, RN starts to transfer data to the UAV, and the UAV stores data to the UAV buffer memory. For data transfer from RN to UAV, both nodes need to satisfy the following conditions:

$$h = 2R_c \sin\left(\frac{\pi}{2} - \alpha\right) = 2R_c \cos(\alpha) \quad \text{and } d_c = 2\sqrt{R_c^2 - h^2}, \tag{15}$$

where R_c is the communication range of an RN, α is the angle between the vertical line and intersection point of the communication point of the communication range circle of RN, d_c is the distance traversed by the UAV in passing over an RN when they are in communication range, and h is the height of UAV from the ground station. The time conditions

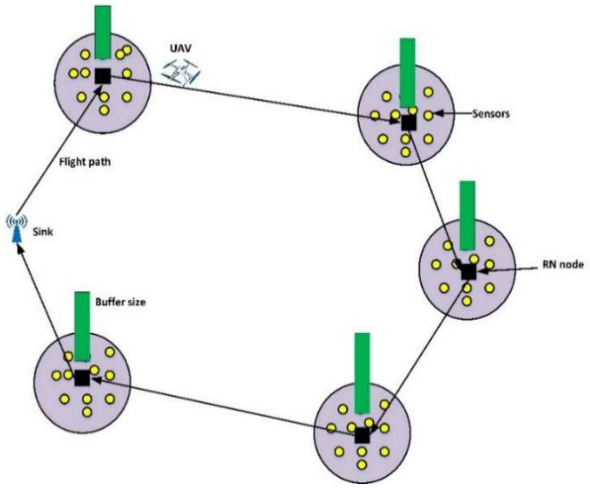


FIGURE 8. UAV-based data collection in cluster network.

for data transfer from RN to UAV have to meet the following condition:

$$s \leq \frac{Rd_c}{8L}, \qquad (16)$$

where L is the length of data, which are exchanged between the RN and UAV. To transfer L number of bytes, the UAV needs to control the minimal speed according to equation 16. After collecting the data from a certain cluster, the UAV uploads the data to the sink node when it finishes the flight time and reaches the sink node. In the same method, the authors also proposed a round-robin UAV routing as shown in Figure 8. In UAV-DC-WSN routing, the UAV moves from one cluster to another in a round-robin scheduling strategy. The UAV moves at a constant speed among the clusters. Communication time is the same for all clusters. If a cluster has more data in the buffer memory, the UAV may collect the data in the next flight cycle.

- Advantages: The UAV-DC-WSN routing protocol is a multi-path cluster routing, which can provide reliability of the network in case of node failure and can tolerate long delays.
- Limitations: The contact time between the UAV and RN node is fixed if RN has a huge buffer, but the UAV cannot take all data at one time because of the time limit. RN needs to wait for the next cycle, which causes an extra delay in the network.
- Potential application: The UAV-DC-WSN routing model can be used for applications where data can tolerate larger delays.
- Possible future improvements: The UAV-DC-WSN routing protocol is designed for data collection in WSNs with a single UAV. In the future, using multi-UAVs may increase the network throughput and decrease the routing delay significantly.

B. CLUSTER-BASED ROUTING PROTOCOLS BASED ON DETERMINISTIC CLUSTERING

In deterministic cluster-based routing protocols, metrics that are more confident are used to elect a CH. The most common metrics are residual energy, centrality, proximity, and node degree. Nodes obtain information from neighboring nodes by overhearing and exchanging messages.

1) DENSITY-BASED SPATIAL CLUSTERING OF APPLICATION WITH NOISE (DBSCAN)

Farmani *et al.* [53] proposed a distributive incorporated clustering algorithm for UAV networks. DBSCAN used extended Kalman filters (EKFs) to estimate the location of mobile targets. The goal of DBSCAN is to create an optimal sensor manager and optimal path planner to track multiple mobile agents. The clustering approach is a suitable solution to overcome computational and communication challenges. In the clustering method, the first step is to facilitate the sensing and communication of UAVs by a distinct constructing group of targets. The DBSCAN routing looks for accuracy of geo-localization of targets. In their study, the authors proposed a distributed method, which takes the advantages of a dynamic weight graph and model predictive control based on the density of target information.

For the geo-localization, EKFs are used to estimate the position and velocity of a target. It is assumed that each UAV is equipped with a noisy GPS and IMU. By applying the coordinate transformation system position, the k-th target is calculated as

$$p_k^i = p_u^i + L\left(R_b^i R_g^b R_c^g l_k^c\right), \qquad (17)$$

where i, b, g, c, and u represent the inertial frame, body frame, gimbal frame, camera frame, and UAV position, respectively. Here, p_u^i represents the position of the UAV inertial coordinate frame, L the length of UAV positon to target, l_k^c the normal vector of target k, R_b^i the vehicle body frame, R_g^b the gimbal frame, and R_c^g the camera frame. In the process of cluster formation, DBSCAN forms clusters with different sizes and arbitrary shapes without any primary information about the data. Generated clusters depend on the order of the data evaluated and require a minimum number of points called *minPts*. The maximum distance ε around a point x is used to identify data within the same cluster. The DBSCAN algorithm uses the local density of data to find the clusters. The distance of ε- *neighborhood* of x is given as

$$N_\varepsilon = \{\mathrm{y} | \delta(\mathrm{x}, \mathrm{y}) \leq \varepsilon, \qquad (18)$$

where $\delta(\mathrm{x}, \mathrm{y})$ is the Euclidean distance between nodes x and y. Figure 9 shows the three different types of points using *minPts*.

- Advantages: In DBSCAN routing, the UAV selects the cluster and obtains the position and velocity of the CM. Once the UAV selects a cluster, it uses the optimal sensor manager and path planner to obtain the geo-located targets within the cluster.

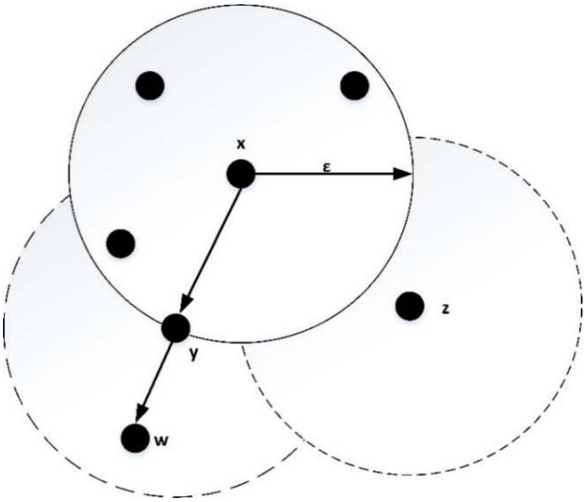


FIGURE 9. Three types of points in the cluster using *minPts*.

- Limitations: In DBSCAN routing, UAVs fly at a constant altitude of approximately 100 m above the ground, which is lower compared with real-time scenarios, and the speed of UAV is 13 m/s.
- Potential application: The DBSCAN routing protocol can be used for vehicular networks to detect fast moving targets and UAV-aided target tracking systems to detect objects.
- Possible future improvements: In the future, it may be possible to update DBSCAN with the next generation of distributed multi-target tracking systems to incorporate the communication bandwidth limits and intermittent communication challenges.

2) CLUSTER-BASED LOCATION-AIDED DYNAMIC SOURCE ROUTING (CBLADSR)

Shi and Luo [54] proposed a location-aided cluster-based routing called CBLADSR, which is a node-weight heuristic-based routing. In the process of clustering, a node-weight heuristic algorithm is used to elect the CH and cluster formation. The CBLADSR process is a combination of intra-cluster routing and inter-cluster routing, which represent short- and long-range communications, respectively. CBLADSR aims to provide significant success in packet delivery ratio and lower end-to-end delay.

The CH election is based on a node-weight heuristic algorithm, where node weights are evaluated according to some factors. Some weight factors such as suitability of node action as a CH, connectivity degree, relative speed of node, and residual energy need to be considered in making a CH. In the process of routing, CMs work only in intra-cluster communication, and CHs work for inter-cluster communication. It is assumed that all nodes are equipped with GPS. GPS provides the node location information, and GPS position information needs to make a node distribution decision in the network. The node-weight heuristic assigns the node weight as

$$W_i = w_{i,1}C_i + w_{i,2}S_i + w_{i,3}E_i + w_{i,4}T_i, \tag{19}$$

where C_i, S_i, E_i, and T_i represent the connectivity degree, relative speed, residual energy, and equipment-dependent tactical value of node i, respectively, and $w_{i,1}$, $w_{i,2}$, $w_{i,3}$, and $w_{i,4}$ are weight factors determined by application scenarios, which satisfy the normalized formula of $w_1 + w_2 + w_3 + w_4 = 1$.

All CMs in the network participate in the CH election process. If a CM node satisfies the residual energy threshold, the CM carries a large weight factor and becomes a CH. CM has information of all neighboring nodes in the neighbor table. The neighbor table contains the status table, CM table, CH table, and temporary table. When a node needs to transmit data to another node of the same cluster, it follows the neighbor table. The neighbor table contains the node location information. Inter-cluster communication is employed through the location-aware dynamic source routing called LADSR. When the destination is a different cluster, the source node sends a packet to its own CH using a short-range communication. Then, the source CH looks at its own routing table and obtains information about destination CH. If the destination CH is far from the source CH, or the location of destination CH is not satisfactory, the source CH sends a route request packet to all CHs for the direction of destination CH. After receiving the route request, the destination CH replays a route request with location information.

- Advantages: Location-aware routing is a promising approach in UAV networks. CBLADSR performs well in long-range and short communication.
- Limitations: In CBLADSR, the residual energy factor is considered as a top weight value, but for the backup CH, the second largest weight factor is not very clear. In the route discovery process, a long delay may occur.
- Potential application: CBLADSR can be used for long-range UAV communications.
- Possible future improvements: In the future, DBSCAN may be extended with more location accuracy for packet forwarding.

3) MOBILITY PREDICTION CLUSTER ALGORITHM (MPCA)

Zang and Zang [55] proposed the MPCA, which is a combination of the dictionary structure prediction algorithm and link expiration time mobility clustering algorithm. Node mobility is considered as a weight metric in MPCA. It is assumed that all nodes have a GPS with a network time protocol system. GPS provides the location and mobility of the node to calculate the link expiration time (LET) between two nodes. If two nodes move in a straight line, the space between the two nodes after time t is radius r. If the nodes are continuously moving, the distance between them may become greater than the transmission range r. The time t represents the LET of two nodes, which is defined as

$$LET = \frac{-(ab+cd) + \sqrt{\left(a^2+c^2\right) r^2 - (ad-bc)^2}}{a^2+c^2}, \tag{20}$$

where $a = V_m Cos\theta_m - V_n Cos\theta_n$, $b = X_m - X_n$, $c = V_m Sin\theta_m - V_n Sin\theta_n$, and $d = Y_m - Y_n$. Furthermore, m and n

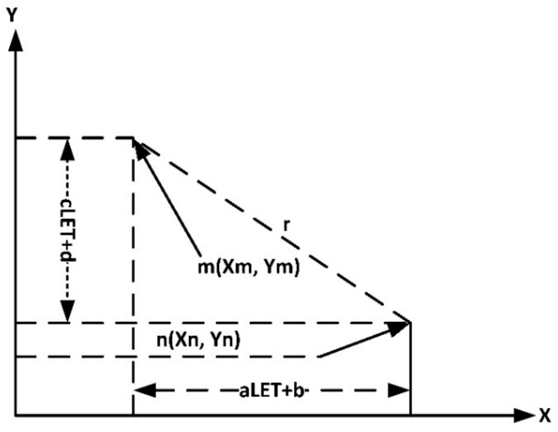


FIGURE 10. Diagram for calculation of LET.

are two nodes within the transmission range of each other, (X_m, Y_m) and (X_n, Y_n) are coordinates of nodes m and n, V_m and V_n are the average speeds of m and n, and θ_m and θ_n are the mobile angle of the nodes, respectively. The LET calculation is shown in Figure 10.

In the process of clustering, CH needs to more stable than all neighbors around it. The weight of each mobile node is defined as

$$W_i = c_1 * P\left(Neighbor_i\right) * d_i + c_2 * avg_{-d_i} + c_3 * LET_i, \tag{21}$$

where $P(Neighbor_i)$ is the probabilty of a set of neighboring node i maintaining the current status, d_i is the connectivity degree of node i, avg_{-d_i} is the average connecitvity degree of node i, and coefficient c_1, c_2, and c_3 are weighting factors.

In the MPCA clustering process, each node is given a globally unique node ID. After taking the position of the node, it broadcasts the ID, current location, and mobile information into a *Hello* packet to its neighboring nodes. In the CH election process, the largest weight node broadcasts a "CH announcement" message to its neighboring nodes and becomes a CH. If one node receives several "CH announcement" messages, it will join with the CH that has a longer LET value.

- Advantages: The node prediction-aware routing is a promising approach in high mobility networks. The MPCA routing can be performed well in high mobility UAV networks with acceptable location accuracy.
- Limitations: The number of CHs in MPCA routing steadily increases with an increase in CMs; thus, the number of single CH may increase. Higher routing overhead due to frequent update of cluster topology.
- Potential application: MPCA routing is suitable for high-speed UAV peer-to-peer communications.
- Possible future improvements: In the future, MPCA may be improved with a precise location prediction for packet forwarding.

4) CLUSTERING ALGORITHM FOR UAVs (CA-UAV)

Liu *et al.* [56] proposed a clustering algorithm for UAV networking in near-space routing called CA-UAV, which aims to guarantee the movable networking ability of nodes in space by reducing the calculation of nodes and adopting a space–earth-based integration through calculation of the ground and adjustment in space.

In the process of clustering, the 3D coordinates of UAV nodes are divided into different areas. The UAV nodes move to each area in between the upper and lower bounds of the cluster size. A weight metrics algorithm is used to elect the CH. When the node-to-node distance is not larger than the effective communication range r, the routing considers only i, j points. The coordinates, moving speed, and moving direction of each node are considered in calculating the connection endurance time from node to node, which is defined as (22), as shown at the bottom of this page, where

$$\begin{aligned} a &= V_i Cos\theta_i(t) Cos\theta_i(t) - V_j Cos\theta_j(t) Cos\theta_j(t), \\ b &= X_i(t) - X_j(t), \\ c &= V_i Cos\theta_i(t) Sin\theta_i(t) - V_j Cos\theta_j(t) Sin\theta_j(t), \\ d &= Y_i\left(t\right) - Y_j\left(t\right), \quad e = V_i Sin\theta_i(t) - V_j Sin\theta_j(t), \end{aligned}$$

and $f = Z_i(t) - Z_j(t)$. Here, X_i, Y_i, Z_i and X_j, Y_j, Z_j are the coordinates of nodes i and j, respectively. $V_i and V_j$ are the average moving speeds, and $\theta_i and \theta_j$ are the moving directions of nodes i and j, respectively.

Node weights assigned to the weight matrix should satisfy the normalized formula $Q = a\,[A] + b\,[B] + c\,[C] + d\,[D]$, where A, B, C, and D represent the node weight factors. All weight factors need to satisfy the condition of $(a + b + c + d = 1$ and $a > b > c > d)$ for each cluster. The node with the highest weight is considered as the CH.

- Advantages: The CA-UAV routing can solve the space–earth integration problem in UAV networks and the algorithm can effectively increase the stability and flexibility of near-space clustering.
- Limitations: In CA-UAV routing, only the UAV position matrix is considered as a high-weight factor.
- Potential application: The CA-UAV routing is suitable for space and ground dynamic communications.
- Future improvements: In the future, CA-UAV may be extended to perform accurate location prediction for packet forwarding.

$$r_{ij}\left(t\right) = \frac{-\left(ab + cd + ef\right) + \sqrt{\left(a^2 + c^2 + e^3\right) r^2 - \left(ad + cd + ef\right)^2 - \left(a^2 + c^2 + e^3\right)\left(b^2 + d^2 + f^3\right)}}{a^2 + c^2 + c^2}, \tag{22}$$

5) LOCALIZATION MULTI-HOP HIERARCHICAL ROUTING (IMRL)

Khelifi *et al.* [57] proposed a fuzzy-based cluster routing algorithm called IMRL, which is more efficient than the existing solutions on energy efficiency, localization accuracy, and data transmission. The IMRL routing relies on a weighted centroid localization method, where UAV node positions are calculated using a fuzzy logic inference depending on the RSSI values.

The data routing proposed method is based on the localization of nodes using weighted centroid localization. RSSI values between the nodes to compute their locations and measurement of the flow through a wireless channel are used to determine the distance between the UAV and anchor UAV node. In IMRL routing, the authors mainly used the location of nodes to elect the next-hop CH. Because of using an efficient transmission of data, ultimately, the energy consumption is reduced and the network lifetime is improved. In the process of fuzzy-based localization algorithm, at the first step, the authors proposed a range-free UAV localization method based on a fuzzy interface. The RSSI value is used to obtain the unknown UAV node positions. After the cluster is formed, UAVs follow predefined paths to scan the area and receive signals from other UAVs. After obtaining all RSSI signals, the distance is calculated using the RSSI values and signal propagation model. Due to the noise of RSSI, it is difficult to determine the accurate position of the UAV.

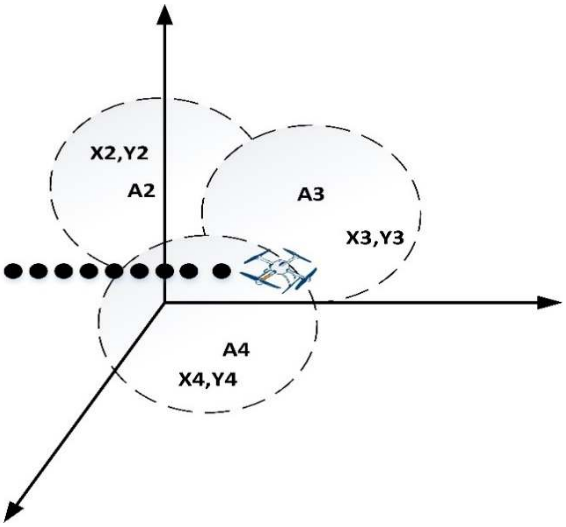


FIGURE 11. **Weighted centroid method.**

To increase the location accuracy, the authors proposed to estimate the UAV location using an edge weight estimation, which is shown in Figure 11. After estimating the location of the node by the localization algorithm, the next step is to elect the next-hop CH for transmitting the data effectively. In the CH election, the largest surplus energy is taken into consideration. The main goal is to share the energy dissipation among all CMs. The CH is responsible for transferring data from the CMs to the base station using a multi-hop transmission. The CH rotation is based on a weighting function.

- Advantages: IMRL routing can be effectively used in bad weather when GPS signal could be totally absent or insufficient due to multi-path fading and jamming.
- Limitations: High latency of transmission and cost of launching the satellite are the major drawbacks of IMRL routing.
- Potential application: IMRL routing is suitable for space and ground dynamic communications.
- Possible future improvements: IMRL routing is designed only for the outdoor scenario. In the future, the IMRL can be performed on indoor scenarios, where radio signals suffer from multiple reflections and multipath padding.

6) TRAFFIC-DIFFERENTIATED ROUTING (TDR)

Qi *et al.* [58] proposed a centralized traffic- differentiated cluster routing called TDR, which aims to address delay-sensitive and reliability-requisite services. A new transmission reliability prediction model is introduced in TDR, which considers both link availability and node forwarding ability.

In the TDR protocol, all UAVs are grouped into several clusters, and an upper stationary UAV controls each of the clusters. It is assumed that all UAV nodes are aware of their positions and speeds through an internal GPS. The controller can realize interactions with all UAVs in the cluster, and it can obtain the UAV position and speed through the *Hello* and *ECHO* messages. For the link availability prediction, it is assumed that the maximum transmission range of all UAV nodes has been known previously, and the location of each node is known through the GPS. There are two UAV nodes, n_i and n_j, and both nodes have an equal radio transmission range d_{max}. The t_0 positions of n_i and n_j are denoted as (x_i, y_i, z_i) and $\left(x_j, y_j, z_j\right)$, respectively. The velocities of n_i and n_j are represented by (v_{xi}, v_{yi}, v_{zi}) and (v_{xj}, v_{yj}, x_{zj}), respectively. The distance can be obtained as

$$d_{ij}\,(t_0) = [(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2] \tag{23}$$

Without any change in velocity, after a certain period t, the distance between n_i and n_j is defined as

$$\begin{aligned} d_{ij}(t_0 + t) = \{&[(x_j + v_{xj}\mathrm{t}) - (x_i + v_{xi}\mathrm{t})]^2 \\ &+ [(y_j + v_{yj}\mathrm{t}) - (y_i + v_{yi}\mathrm{t})]^2 \\ &+ [(z_j + v_{zj}\mathrm{t}) - (z_i + v_{zi}\mathrm{t})]^2\}^{\frac{1}{2}}. \end{aligned} \tag{24}$$

- Advantages: TDR routing performs well in terms of end-to-end delay, lower packet dropping ratio, and network throughput. TDR introduces the transmission reliability prediction.
- Limitations: In TDR routing, the selected paths may not be optimal until the overall performance is not comprehensive. For data forwarding, the selfishness of malicious nodes is not considered, and network load may

increase if numerous probe packets have to be sent in the parameter estimation.
- Potential application: TDR routing can be used for delay-sensitive applications.
- Possible future improvements: TDR routing may be improved by controlling the cost of traffic flow to solve the overhead and energy consumption, and the selfishness of malicious nodes needs to be controlled to minimize the node forwarding failure issue.

7) GRID POSITION NO CENTER SHORTEST PATH ROUTING (GPNC-SP)

Lin *et al.* [59] proposed a shortest path routing algorithm based on the grid position called GPNC-SP. This routing uses a logical grid distance to replace the original Euclidean distance and decrease the sensitivity of fast-moving nodes. GPNC-SP achieves the shortest routing path by automatically computing and adjusting the Dijkstra algorithm and dynamically enhances the routing path of a regional reconstruction strategy. The GPNC-SP routing protocol aims to achieve a better performance in terms of network overhead, link stability, computational complexity, more stable links, and calculation speed.

GPNC-SP is based on a two-dimensional (2D) logical grid partition. Each grid is a $G_w \times G_w$ square size and is signified as (x, y) following the XY-coordinate. There are two nodes i and j, which are located in grids $A(a,b)$ and $B(c, d)$, respectively. Here, (a,b) and (c,d) are the coordinates of grids A and B, respectively. The grid distance between i and j is calculated as

$$D_{ij}^{G} = |AB|^{G} = \sqrt{(|a-c|+1)^2 + (|b-d|+1)^2} \tag{25}$$

In the process of GPNC-SP routing, all nodes obtain the position of each node through a neighbor table. When a node moves after a time interval, every node obtains the new location information through a GPS device and calculates the grid position accordingly. The grid size and partition are calculated as

$$W^{G} = |\frac{W}{G_w}| \quad \text{and } H^{G} = \left|\frac{H}{H_w}\right|, \tag{26}$$

where W^G and H^G are the width (W) and length of S (H) in the logical grid space, respectively. The position of the new location in the logical grid of UAV j at time t is defined as

$$x_j^G(t) = \left[\frac{x_j(t)}{G_w}\right] \in [0, W^G]$$

and

$$y_j^G(t) = \left[\frac{y_j(t)}{G_w}\right] \in [0, H^G], \tag{27}$$

where $x_j^G(t)$ and $y_j^G(t)$ are the grid positions of UAV j at time t. The proposed algorithm is different from that of the conventional grid method. It takes a smaller logical grid to partition the mission of UAV node and replace the geographical position with the relative grid position when the link changes due to the fast movement of UAV node.

- Advantages: In GPNC-SP routing, the size of the logical grid is an important factor in routing performance. GPNC-SP routing is performed well when the grid width is between 0.022–0.055 times of the node communication radius.
- Limitations: In GPNC-SP routing, the connectivity of the link is not very satisfactory, and the tradeoff of the performance improvement of GPNC-SP is some loss on the communication distance of the UAV node.
- Potential application: GPNC-SP routing is suitable for highly dynamic and fast-moving UAV applications.
- Future improvements: The actual mission of UAVs is a 3D space, and extension of the GPNC-SP routing protocol in 3D space should be investigated in the future.

8) MOBILITY PREDICTION CLUSTER ROUTING (MPCR)

Shu *et al.* [60] proposed the cluster routing scheme based on mobility prediction for UAVs, in which message ferrying is introduced with store-carry-forward (SCF) mechanism in MPCR. MPCR elects the CH that has the largest connectivity; therefore, this method reduces the changes of CH. For the disconnected node, MPCR introduces ferry nodes, which forward the message from source to destination. MPCR aims to reduce communication delay and increase the packet delivery ratio in UAV networks.

In the process of cluster formation, the node that has the highest connectivity probability is elected as the CH. The CH maintains a cluster table, which contains all records of its neighboring clusters. The connectivity probability between two nodes is calculated as follows:

$$P = \sum\nolimits_{i=1}^{n} p_{ni}, \tag{28}$$

where n is the number of neighboring nodes, i represents a node, and p_{ni} represents the probability of node availability. MPCR controls the data forwarding of multiple copies during the ferrying of data. The message transmission is classified into three categories: DD, relay, and ferry. In DD, the source node sends data to the destination but if the destination is the neighbor of the source node, the message is recognized as a DD. In relay, if the source node and destination node are in the same cluster, it is called relay. Storing and carrying a message for a period and finally transmitting it to the destination is identified as a ferry. In MPCR, the SCF mechanism is used to relay the data from source to destination. The distance between the nodes and speed of nodes are considered as key factors in MPCR.

- Advantages: MPCR performs well in terms of packet delivery ratio and end-to-end delay.
- Limitations: In MPCR, the probability of the highest connectivity of a node is considered in electing the CH. However, in a highly dynamic network, only the node connectivity has an effect on the CH lifetime.
- Potential application: MPCR is suitable for delay-tolerant network applications.

- Possible future improvements: In the future, MPCR may be extended to merge the disconnected clusters in UAV networks.

IV. COMPARISON OF CLUSTER-BASED ROUTING PROTOCOLS

In this section, the existing cluster-based routing protocols are qualitatively compared in terms of outstanding features, characteristics, competitive advantages, and limitations. The innovative features of existing cluster-based routing protocols are summarized in Table 2, where all the protocols reviewed in Section 3 are presented.

TABLE 2. Innovative features of existing cluster-based routing protocols.

Protocol	Reference	Innovative features
URP	[42]	Dynamic clustering approach
ULSN	[44]	Distributed clustering approach
UAV-WSN	[45]	Distributed clustering approach
EALC	[46]	A bio-inspired routing combination of ant-colony optimization and gray wolf optimization-based clustering approach
BIMPC	[47]	A bio-inspired mobility prediction clustering approach
AC-BC ad hoc	[48]	A bio-inspired probabilistic routing combination of ant-colony and bee-colony algorithm
Bee ad hoc	[49]	A bio-inspired routing based on bee-colony algorithm
ERSUAV	[50]	A bio-inspired routing based on ant-colony algorithm
rHEED	[51]	Dynamic and distributed clustering approach
UAV-DC-WSN	[52]	Delay-tolerant cluster routing based on store-and-forward mechanism
DBSCAN	[53]	Distributed and density-based clustering approach; a location-aided cluster-based routing
CBLADSR	[54]	A cluster-based location-aided dynamic source routing; a node-weight heuristic algorithm used for clustering
MPCA	[55]	A mobility prediction clustering approach
CA-UAV	[56]	A clustering algorithm of near-space UAV networking
IMRL	[57]	Fuzzy logic-based centralized clustering approach
TDR	[58]	A centralized traffic-differentiated cluster-based routing
GPNC-SP	[59]	Logical grid partition-based routing approach
MPCR	[60]	Mobility prediction clustering routing approach combination with store-carry-forward mechanism

In Table 2, the distinct innovative features of each cluster-based routing protocols for UAV networks are listed for the 18 reviewed protocols. From our study, it is found that bio-inspired and fuzzy-logic-based routing protocols achieve a higher performance in comparison to the others in highly dynamic UAV networks.

In Table 3, the existing cluster-based routing protocols are extensively compared with respect to various features, characteristics, and performance metrics. It should be noted that most protocols use GPS to define the geographic location. Few protocols obtain the location information of UAV nodes by using both GPS and RSSI. The design of an appropriate cluster-based routing protocol for a UAV network is strongly dependent on the requirement and application of the UAV network. From our study, weight-based clustering approach is eminent in cluster-based routing for UAV networks because rapid mobility and topology change are inevitable in UAV networks. Cluster formation including CH election needs to consider several factors such as UAV location, velocity, energy condition, and buffer size. Electing an appropriate CH may increase the network lifetime and packet delivery ratio while reducing delay.

V. OPEN RESEARCH ISSUES AND CHALLENGES

In this section, important open research issues and challenges are addressed and discussed. UAV routing protocols are still in their developmental stage. The main 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, which are still challenges for developing a cluster-based routing protocol for UAV networks. Such issues and challenges focus on the improvement of routing scalability, reduction of complexity in cluster-based routing, energy efficiency routing, minimization of routing delay, equal load distribution among nodes, and improvement in routing security. Seven challenging issues are summarized in this section, which will be helpful to researchers and engineers in the field for choosing a routing protocol or developing a new one.

A. LINK DISCONNECTION

Generally, UAVs are deployed in low density and need to move with high mobility. Due to frequent changes in the network topology, the communication nodes are frequently disconnected. This destabilizes the communication network, causing an undesirable impact on the efficiency of routing as well as its performance. Broken connectivity in networks makes routing more complex than its existing state 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 cause packet losses. Connectivity and coverage can be ensured and pursued in cluster-based routing protocols.

B. 3D SCENARIOS

Most of the UAV routings are usually deployed on a 2D surface, whereas UAVs are moving in 3D space. The main challenge in 3D UAV routing is to manage the UAV node mobility. In multi-UAV networks, communication among UAVs in 3D space considering crucial features is required to increase routing efficiency. In 3D UAV networks, architecture-based swarms of UAV lead to ample new application scenarios.

TABLE 3. Comparison of cluster-based routing protocols.

Protocol	Year	Cluster size	Intra-cluster comm.	Inter-cluster comm.	CH mobility	CH type	CH role	Clustering method	CH election
URP	2018	Equal	1-hop	k-hop	Stationary	Heterogeneous	Relay	Dynamic	Dynamic
ULSN	2013	Unequal	k-hop	k-hop	Stationary	Heterogeneous	Relay	Distributed	Random
UAV-WSN	2012	Unequal	1-hop	1-hop	Stationary	Heterogeneous	Aggregation	Distributed	Random
EALC	2018	Equal	k-hop	k-hop	Movable	Homogeneous	Relay	k-means	Weighted metrics-based
BIMPC	2016	Unequal	1-hop	k-hop	Movable	Homogeneous	Aggregation	Distributed	Hybrid
AC-BC ad hoc	2016	Unequal	1-hop	k-hop	Movable	Heterogeneous	Aggregation	Hybrid	Probabilistic
Bee ad hoc	2016	Unequal	1-hop	k-hop	Movable	Heterogeneous	Aggregation	Distributed	Probabilistic
ERSUAV	2016	Equal	k-hop	k-hop	Stationary	Heterogeneous	Aggregation	Centralized	Deterministic (by BS)
rHEED	2014	Equal	1-hop	k-hop	Stationary	Heterogeneous	Relay	Distributed	Hybrid
UAV-DC-WSN	2015	Equal	1-hop	k-hop	Stationary	Heterogeneous	Relay	Centralized	Hybrid
DBSCAN	2017	Unequal	1-hop	k-hop	Movable	Heterogeneous	Aggregation	Distributed	Weighted metrics-based
CBLADSR	2012	Equal	1-hop	k-hop	Movable	Homogeneous	Relay	Distributed	Weighted metrics-based
MPCA	2011	Equal	1-hop	1-hop	Movable	Homogeneous	Relay	Dynamic	Weighted metrics-based
CA-UAV	2008	Unequal	1-hop	k-hop	Movable	Heterogeneous	Aggregation	Dynamic	Weighted metrics-based
IMRL	2018	Equal	1-hop	k-hop	Movable	Homogeneous	Relay	Centralized	Weighted metrics-based
TDR	2017	Equal	k-hop	1-hop	Movable	Heterogeneous	Relay	Centralized	Weighted metrics-based
GPNC-SP	2017	Equal	k-hop	k-hop	Movable	Homogeneous	Aggregation	Centralized	Compound
MPCR	2011	Unequal	1-hop	k-hop	Movable	Heterogeneous	Relay	Dynamic	Probabilistic

TABLE 3. ***(Continued.)*** **Comparison of cluster-based routing protocols.**

Protocol	Topology	Data transmission	Location awareness	Scalability	Fault tolerance	Comm. reliability	End-to-end delay	Protocol complexity
URP	Hierarchical	Single-hop	Yes	–	No	–	–	Moderate
ULSN	Hierarchical	Multi-hop	No	–	Yes	Yes	Low	Moderate
UAV-WSN	Hierarchical	Single -hop	No	–	–	–	–	Moderate
EALC	Grid	Multi-hop	No	–	–	–	Low	Moderate
BIMPC	Ad hoc	Single-hop	Yes	Yes	–	Yes	Low	High
AC-BC ad hoc	Ad hoc	Multi-hop	No	Yes	Yes	Yes	Medium	Moderate
Bee ad hoc	Hierarchical	Multi-hop	Yes	Yes	–	Yes	High	Moderate
ERSUAV	Hierarchical	Multi-hop	Yes	–	–	–	Medium	Moderate
rHEED	Hierarchical	Multi-hop	No	Yes	No	Yes	Low	Moderate
UAV-DC-WSN	Hierarchical	Multi-hop	No	Yes	Yes	Yes	–	High
DBSCAN	Hierarchical	Multi-hop	Yes	Yes	–	–	–	High
CBLADSR	Hierarchical	Single-hop	Yes	Yes	Yes	Yes	Low	Moderate
MPCA	Hierarchical	Single-hop	Yes	Yes	–	–	–	Low
CA-UAV	Hierarchical	Multi-hop	No	Yes	–	–	–	Low
IMRL	Hierarchical	Multi-hop	Yes	Yes	No	–	High	Moderate
TDR	Hierarchical	Traffic differentiated	Yes	Yes	Yes	Yes	Low	High
GPNC-SP	Grid	Multi-hop	Yes	Yes	No	No	Low	High
MPCR	Hierarchical	Single-hop	Yes	Yes	Yes	Yes	Low	Low

Note: "–" means not specified in the corresponding literature

C. PERFORMANCE AWARENESS

In UAV networks, efficient data exchange between UAVs is difficult, and the network properties are entirely different from those of MANETs and VANETs. One of the significant drawbacks is that the simulation results of UAVs at high-speed motions show additional delay. The delay threshold is considered a challenging issue. The main challenge in the routing supporting the mobility is that the protocol should be able to handle the overhead when the nodes are mobile and the topology changes frequently in the network. In addition, the estimation of link prediction, link establishment, and cluster formation is also a challenging task in a routing protocol. Most of the routing protocols are bound to issues related to delays and overhead. There are many possible metrics to consider for routing. Designing an efficient routing protocol and additional metrics, such as route mobility, QoS metrics, stability, link quality, and security metrics, may be considered.

D. EVALUATION TOOLS

A good number of simulation tools are used for routing protocol simulations of UAV networks. The majority of them do not show realistic or reasonable results. MATLAB, OPNET, NS-2, and OMNET++ are the most common tools for performance measurement and evaluation of cluster-based routing protocols in UAV networks. 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 researchers use personalized simulators that do not support the reuse of codes. Therefore, a new simulation tool that supports more realistic mobility models and predefined mobility to obtain more reasonable and realistic outputs is required to design cluster-based routing protocols in UAV networks.

E. SECURITY

Security has been yet another concern for cluster-based UAV routing protocols. Network layers are the building blocks of a network; thus, future security concerns need to be considered when designing routing protocols, as UAVs are capable of hijacking and can be used as weapons or other applications that can cause damages. An authentication node may be used to protect UAVs from internal or external attacks. Additional security methods may be applied to make the routing protocol more secure. Further study is required in network layering of cluster routing to ensure security and preventing network attacks, such as *Hello* packet, spoofing, and denial of service. To increase security, CHs can perform security protocols and data acquisition. Compared to conventional public key-based system encryption, hashing techniques are more suitable and more secure.

F. COLLABORATION AND COORDINATION AMONG UAVs

For avoiding collision between multiple UAVs, collaboration and coordination among UAVs are essential. For large-scale UAV networks and multi-UAV operation, cooperation and coordination between UAVs are essential for increasing the routing efficiency. Dynamic path planning is required to enhance the UAV communication. Minimizing the end-to-end delay between UAVs in dense deployment remains an important research issue.

G. QUALITY OF SERVICE

Meeting the QoS requirements in UAV routing is another open challenge. For supporting a better QoS, fault tolerance is required in some applications, which can be executed by the CHs. Highly accurate GPS location information is essential for UAV routing. Still, localization in UAV routing protocol is a challenging task. Particularly in cluster-based UAV routing, localization is important to reduce the single CH and increase the CH lifetime.

VI. CONCLUSION

In UAV networks, routing plays a key role in cooperative and collaborative network operations. Over the past few years, many cluster-based routing protocols for UAV networks have been reported in the literature. In this article, we have surveyed cluster-based routing protocols for UAV networks and compared them qualitatively in terms of outstanding features, characteristics, competitive advantages, and limitations. Our work is a comprehensive and state-of-the-art survey on cluster-based routing protocols for UAV networks. The 18 cluster-based routing protocols for UAV networks are systematically classified according to the underlying clustering mechanism, and they are then compared with each other based on some primary metrics such as various clustering techniques, cluster mobility, CH election, energy efficiency, data transmission, and end-to-end delay. This comparison results may help researchers and engineers to choose the most appropriate cluster-based routing protocol based on their requirements. From the comparative study, it is found that each routing protocol has its particular strengths, limitations, and suitability to specific applications. In addition, important open research issues and challenges on cluster-based routing for UAV networks are summarized and discussed.

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