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SURVEY

A Fresh Look at Routing Protocols in Unmanned Aerial Vehicular Networks: A Survey

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ABSTRACT The use of Unmanned Aerial Vehicles (UAVs) or drones has grown rapidly in both civilian and military operations over the last few decades. Multi-UAV systems are preferred to single-UAV systems, as they are more efficient and cost-effective when completing missions collaboratively. However, like other ad-hoc networks, UAV networks face the challenge of effective communication. Existing research in mobile ad-hoc networks (MANETs) and vehicular ad-hoc networks (VANETs) does not fully address the unique characteristics of UAV networks, which can exhibit varying levels of dynamism, intermittent links, and fluid topology. Moreover, drones need to communicate with each other and ground stations in Flying Ad-hoc Networks. Therefore, routing protocols in such networks must select the most effective paths for communication while ensuring reliable and stable data transmission. This article examines several recently developed routing protocols in UAV communication, detailing their construction methods. As routing is quite challenging in UAVs, where communication performance depends on various factors, this research introduces performance metrics to analyze the efficiency of these protocols. Routing protocols in UAV networks must adapt to high mobility, dynamic topology, intermittent links, power constraints, and changing link quality. Since the lifespan of UAV nodes is limited, seamless handovers are crucial, and the energy efficiency of protocols at different layers should also be considered. Although the reviewed protocols address several aspects of designing routing protocols for UAV communication, some challenges remain. Thus, this article provides a comprehensive exploration of routing protocols in UAV communication, along with a discussion of some open research areas.

INDEX TERMS Unmanned aerial vehicle, routing protocol, FANET, ad-hoc network, multi-path communication.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have emerged as a significant technological advancement in recent years due to their versatility and ability to perform tasks that would otherwise be too dangerous or time-consuming for airmen [1], [2], [3]. These aircraft are piloted remotely or autonomously and have numerous applications ranging from military reconnaissance to disaster management and surveillance [4], [5], [6], [7]. These flying machines can communicate among themselves by forming the Flying Ad-hoc Networks (FANETs) [8], [9]. Thus, the UAVs are designed to fly without a human pilot on board and can be controlled by operators on the ground using a remote control or by using pre-programmed algorithms [10], [11]. Besides, the rapid advancement of materials, sensors, and computing power, UAV technology is now offering a greater range, endurance, and functionality [12], [13].

Each UAV is equipped with a communication module, comprising a transceiver and an antenna, which can operate various technologies, including RF, satellite, and cellular, to communicate with each other and the ground station [14], [15]. The transceiver transmits and receives data, while the antenna acts as the module's interface with the

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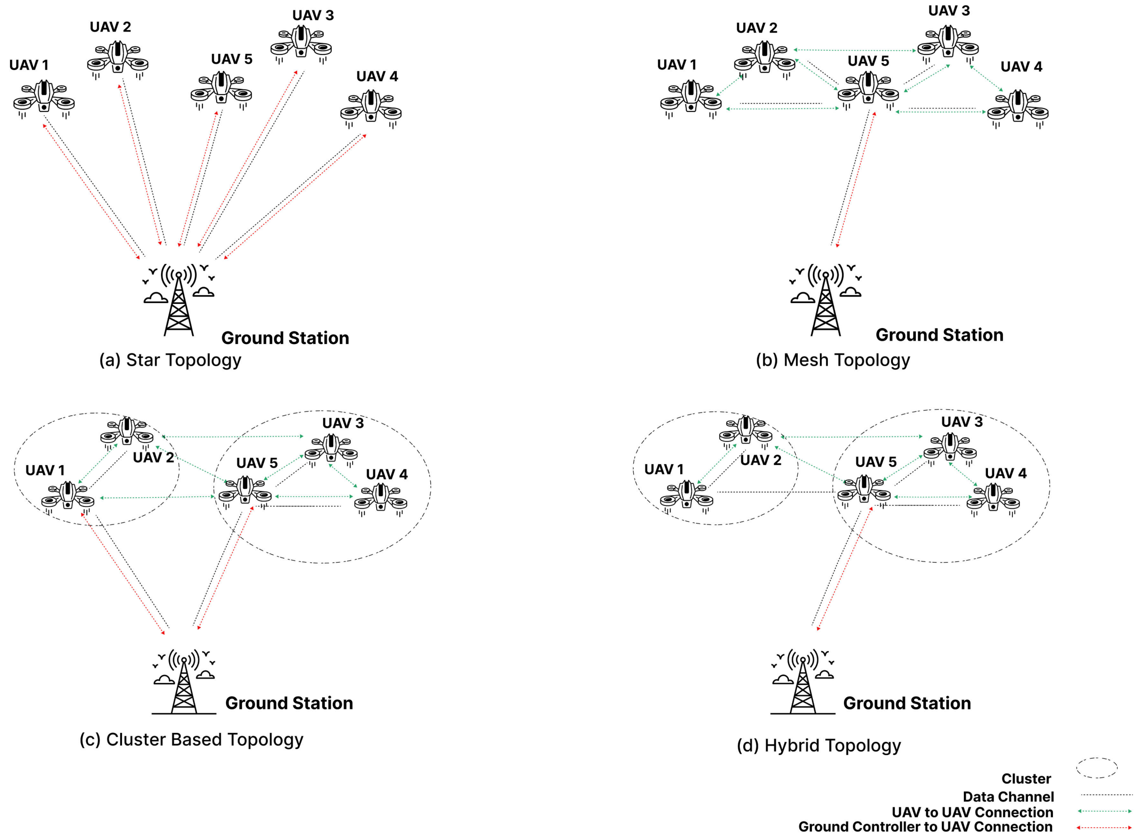

FIGURE 1. UAV communication topology.

environment [16]. Figure 1 shows how the wireless module operates on specific frequencies to facilitate communication with other UAVs or ground stations. Figure 1(a) shows a particular structure of the network denoted as a star topology, in which the ground station is directly connected with every UAV, which can be considered as a node. In this way, the ground station can send and receive data packets from every UAV. However in Figure 1(b), the ground station is only connected to a single node, which is the cluster head of the UAV group. This cluster head passes the data packets from the ground station to the other member nodes as well as the other way around. This structure of the network is known as mesh topology. In Figure 1(c), cluster-based network topology has been shown where the ground station is connected to two UAVs, which are the heads of their respective cluster. These heads are collecting data packets from the member UAVs to forward them to the ground station, and vice versa. Figure 1(d) shows a hybrid mesh network, in which the cluster head UAV is connected to the ground station. Here, the head can not only pass the information to the UAVs of its group but also pass information to other nearby cluster heads. The head is also able to pass information from the ground station to other connected nodes and vice-versa. So we can understand from these diagrams that the ground station can be connected to multiple UAVs where they can be single or group cluster heads. Also, the cluster heads can share information with their groups, UAVs, or the head UAVs of another group. RF communication is typically used by UAVs for wireless connection with the ground station.

In order for unmanned aerial vehicles (UAVs) to accomplish their tasks, they must engage in communication with both other UAVs and a ground station. This communication requires a reliable and efficient routing mechanism that ensures the delivery of data packets to the destination while avoiding collisions with other UAVs and obstacles [8]. Therefore, a key element of any UAV system is the routing protocol, which regulates communication between different nodes within the network and ensures efficient and effective transmission of data [17]. As UAVs become more prevalent in various industries, the need for robust and reliable routing protocols becomes more pressing.

The design of routing protocols for UAV communication is a challenging task, especially in dynamic scenarios with high mobility and high network density [18], [19]. When creating a routing protocol for UAVs, several parameters such as end-to-end delay, throughput, and dynamic topology must be taken into consideration [20], [21], [22]. Communication among UAVs should have low energy consumption while still upholding a high standard of service, which is a considerable challenge in this field [23], [24]. The protocols must also guarantee secure, dependable, and reliable data transmission [18], [25], [26]. Hence, an autonomous, intelligent, and efficient routing protocol is required to deal with the changes in network density and topology.

In recent years, the field of UAV routing protocols has seen the emergence of several survey papers, each offering its unique contributions and areas of focus. The survey presented in [27] examines UAV routing protocols, with a particular emphasis on network models and categories such as position-based, topology-based, cluster-based, deterministic, stochastic, and social-network-based approaches. It provides coverage of multiple protocols within each category, including data forwarding-based protocols and field experiments. Notably, a uniform set of performance metrics is not included in this survey. In [28], the survey article encompasses UAV classification, communication architectures, application frameworks, and routing protocols. It evaluates the features of these protocols and offers guidance for protocol selection. In the context of radio spectrum management for UAV communications, the survey in [29] delves into versatile techniques, and research challenges, and introduces a proposed hierarchical spectrum management paradigm. Additionally, the survey in [30] delves into UAV swarm communication architectures and routing protocols, conducting a comparative analysis of their strengths, weaknesses, and suitability in different scenarios, while addressing open research issues and presenting spectrum management solutions. On the other hand, [31] focuses on mmWave beamforming-enabled UAV networking and communications, examining technology aspects, antenna structures, channel modeling, and factors like latency, bandwidth, and energy consumption across various application scenarios.

Existing surveys explore routing protocols for UAV networks, categorizing them into position-based, topology-based, cluster-based, deterministic, stochastic, and social-network-based approaches. While they overview and evaluate protocol strengths and weaknesses, some surveys lack uniform performance metrics [27], may not cover the latest advancements [28], or primarily focus on radio spectrum management [29]. Additionally, limitations exist in the analysis of UAV swarm communication architectures and open research challenges [30]. Furthermore, the survey [31] specifically addresses mmWave-UAV communication technology.

This study contributes to the advancement of knowledge in UAV routing, provides a comprehensive evaluation of existing protocols, and opens new avenues for research in the field. The contribution of this survey article stands out in several aspects, highlighting the distinct differences from existing surveys:

- Comprehensive analysis: Comprehensive exploration and analysis of recently developed routing protocols in UAV communication networks, considering the characteristics of UAV networks.
- New performance metrics: Introduction of the new performance metrics to assess the efficiency of routing protocols in UAV networks, focusing on both the communication performance of these routing protocols as well as stability. Furthermore, these new uniform performance metrics enable a standardized comparison.
- Performance analysis based on the metrics: The survey thoroughly evaluates the strengths and limitations of existing UAV routing protocols based on the performance metrics. This also helps to have a comprehensive understanding of UAV routing algorithms.
- Identification of open research areas: The survey identifies open research areas and suggests potential directions for further advancements in UAV routing.

The rest of this article is structured as follows: Section II provides an examination of the relevant literature pertaining to existing routing protocols and networking strategies in UAVs. In Section III, performance metrics are presented with appropriate justification. Section IV details the analysis of the performance of the routing protocols through tabular representation. Section V highlights open research areas and finally, the paper is concluded in Section VI.

II. EXISTING ROUTING PROTOCOLS IN UAV NETWORKS

The field of UAV communication has garnered significant attention in the research community in recent years. To address key concerns related to the practical deployment of UAVs, several routing protocols have been developed. This section aims to explore a range of recently developed routing protocols in the context of UAV communication.

A. BR-AODV ROUTING PROTOCOL

The main focus of this work is the presentation of a novel flocking-based routing protocol for UAVs named Boids of Reynolds Ad Hoc On-Demand Vector (BR-AODV) [32]. The protocol builds upon a widely used ad hoc routing protocol (AODV) for computing routes on demand [34], while also incorporating the Boids of Reynolds (BR) mechanism [35] to maintain connectivity and route management during data transmission. In the BR-AODV navigation system, which is based on Boids, Route Request (RREQ) packets are sent to the location distribution by altering the precise position and transmitting them to the nearest peers of the sender node. If the receivers are not directly connected to the ground point, they forward the RREQ packets. Devices that are directly connected to the ground point send the Route Reply (RREP) packet as a unicast message along the shortest path to the sender. Finally, the source node selects the RREP packet with the nearest terrestrial base point.

This protocol aims to reduce the number of path search requests and simplify the maintenance of effective routes. The application sets a limit known as the duration boundary, i.e., the maximum time is applied here. It is determined which nodes (UAVs) are active or inactive, depending on the duration the node has been in silence, without receiving or transmitting packets. If the duration the node has been in a silence period is greater than the maximum duration threshold, the node is inactive. Conversely, if it is less than or equal to the maximum threshold, the node is active. When a message is sent, the parameter used to count the interval is reset to zero and the duration is counted again. Therefore, if all routers are active, the path is considered active. If a node is down, the test route is deemed inactive. Additionally, other targeted drones with an existing route having terrestrial base points can be considered ground base stations that can receive data from a source aircraft. To establish this connection proactively, a ground base point must be effective in inputting and outputting routing data into the Mobile Ad-hoc Network (MANET) of the UAV. Each land base point broadcasts a unique signal called drone and network association (DNA) for UAVs and a network connection with enough information for the receivers to establish an appropriate routing entry to the closest base points to allow the input of outside routing data into a MANET for UAVs. The DNA signals are limited to one-hop aircraft of the base points due to the network's flexible topology and responsiveness to changes. The ground base stations broadcast signals with enough information for the receivers to build a proper routing input to the nearest base points, allowing input of external routing data into MANET for UAV.

B. REACTIVE-GREEDY-REACTIVE ROUTING PROTOCOL

The Reactive-Greedy-Reactive (RGR) protocol uses *hello* signals to keep track of neighboring nodes' locations and identities [33], [36]. It has four types of control packets: Route Requests (RREQs), Route Replies (RREPs), Route Error (RERR) messages, and *hello* signals. Except for the fact that RREQs, RREPs, and *hello* messages convey geographical data, these signals have the same capabilities as the Ad Hoc On-Demand Distance Vector (AODV) protocol. RGR uses two tables for each node: a routing table that contains information about fixed targets and their addresses, and a neighbor table that contains the position data of every 1-hop neighbor. The neighbor table is updated through regular *hello* packets. When a node receives a message, it checks its routing table to see if it has a reactive or responsive path to the target. If the path has been interrupted or broken, the RGR protocol tries to re-establish it. The positional data carried by RREQs, RREPs, and *hello* messages are used to update the node's databases. If a node receives a message from a greedy or tempted forwarder, it searches its routing table for an appropriate path. If the routing database contains an entry pointing to the endpoint but the node database lacks the next hop neighbor, the node looks through the neighbor database table to find the closest neighbor to the target. If a neighbor node receives a signal, it can transmit it to the target on a reactive or responsive route using Greedy Geographic Forwarding. The protocol allows both origin nodes with a route to the endpoint and those without to transmit signals collected through a reactive route. If at least one transition from Greedy Geographic Forwarding has occurred between the origin and the endpoint, the signal can be transmitted. When the destination node identifies itself as the endpoint, it transmits the message back to the sender. In case the source node initiates a path-searching procedure, it sends RREQ messages to the network and waits for the endpoint node to respond with RREPs. Supposing the RREP messages reach the source node, a genuine reactive route will be established, allowing the node to learn the location of the target node. However, assuming that the route becomes inactive after a short period, a new path-searching technique may need to be used for the same destination. This technique uses the velocity vector of the next hop node, associated with a specific time, to predict the distance between the current node and the next hop before broadcasting messages. If the next hop node leaves the communication range, the current node can immediately respond by rejecting the reactive route's condition and switching to Greedy Geographic Forwarding to preserve the messages that would have otherwise been lost.

C. SMART IoT CONTROL-BASED NATURE INSPIRED ENERGY EFFICIENT ROUTING PROTOCOL (eAntHocNet)

eAntHocNet [37] is a meta-heuristic protocol that is used in ant colonies. Environmental algorithms are recursive, i.e., they maintain a path repeatedly to discover the perfect result. With each repetition, the ants create the latest viable options. The likelihood of an ant selecting node 'j' from node 'i' in each cycle is provided by equation 1.

$$P_{i,j}^{k} = \frac{\left(\tau_{i,j}^{a} * \eta_{i,j}^{\beta}\right)}{\sum_{t \in N_i}\left(\tau_{i,j}^{a} * \eta_{i,j}^{\beta}\right)} \tag{1}$$

where $P_{i,j}^{k}$ is the potluck of alteration of the k_{th} ant by utilizing link l from vertex 'i' to 'j'. $\tau_{i},_{j}$ is the amount of pheromone on I. $\eta_{i,j}$ is the value of the heuristic of link l that is usually $\frac{1}{d_{i,j}}$, where $d_{i},_{j}$ is the Euclidean space between 'i' and 'j'. The neighbor of node 'i' is N_i, and here α and β are weighting variables representing the importance of the pheromone and the range in selecting the following vertex. Daemon activities are optional procedures that can be used to conduct specific actions related to a challenge or situation. Typically, daemon operations are called after the solution creation stage. The goal of the pheromone update procedure is to increase the value of T for good solutions. For poor solutions, the value of T is low. However, in most cases, it is achieved through pheromone evaporation, where the intensity of the pheromone is reduced for all routes to prevent early convergence on a sub-optimal solution. The pheromone update performed by the Ant Colony Optimization algorithm is described in equation 2.

$$\tau_{i,j}(t+1) = (1-\rho) \times \tau_{i,j}(t) + \sum_{k=1}^{m} \Delta\tau_{i,j}^{k}(t) \tag{2}$$

Here, $1 \leq \rho \leq 1$ is the evaporation rate, the number of nodes is given by m, and the amount of pheromone that laid at i, j is given by $\tau_{i,j}^{k}$.

D. JAMMING RESILIENT MULTIPATH ROUTING (JarmRout) PROTOCOL

In the JarmRout protocol [38], if a source node has information signals to transmit, it will first search its routing database for the route to the destination node. The path-searching process begins with the sender node sending a Route Request (RREQ) signal when the path is not available. The RREQ includes the source node identification, destination node identification, signal sequence number, count of nodes along the sender path, sender path note, collection of location coordinates of nodes, lowest connection performance along the path, and highest throughput load along the path. When an intermediate node receives an RREQ, it saves the message serial number and the number of steps to the sender node in its cache. It also determines the performance of the connection between itself and the RREQ transmitter, as well as the presence of traffic nodes. However, in this protocol, intermediate nodes are not authorized to transmit the Route Reply (RREP) signal back to the sender node, even if they contain routing data to the destination. At the destination node, a database or table of the route contains information about accepted different node disjoint paths. When the destination node receives the first Route Request signal, it records the sequence number, sender route record, collection of location coordinates of nodes, lowest connection performance along the path, and highest traffic load along the path in the connection database. The destination node then waits for a set amount of time for more Route Request messages to arrive and learn about all available connections. Specific routes can frequently become disconnected due to node movements, packet conflicts, traffic congestion, and disruption. If a node fails to transmit a message to the next hop node along the available route regularly, it perceives the connection to be separated and sends a Route Error (RERR) message.

E. COURSE-AWARE OPPORTUNISTIC ROUTING PROTOCOL (CORF)

The CORF protocol in [39] consists of two stages. In the first stage, the sending UAV establishes the flight path between nodes and uses transmission probabilities as auxiliary data to dynamically select a relay node. Dijkstra's Method can be employed to find the shortest route. During the second stage, the UAV follows the predetermined path to avoid collisions with other UAVs. The Public Information (PI) packet contains several parameters including vector, location, sender, time to live, and payload. The Acknowledgement (ACK) packet has three components: vector, location, and quantity. The protocol requires the PI node to transmit data to its neighbors periodically and determine whether to transmit based on the received ACK. The protocol employs a two-stage approach that combines the computation of direction and transfer probability to make decisions about selecting the relay node. The protocol uses one-step regional architectural data to choose the relay node based on the current location of the UAVs. The Ground Station (GS) acts as a relay node between two UAVs, and this concept can be extended to other scenarios. When moving in opposite directions, the UAV and the GS are in two relative phases, in which the protocol can be determined by calculating the angular connection and movement vector. Based on the directional data and transfer probability, the sender node may select an adjacent UAV or GS as the next-step relay.

F. LOCATION-AGNOSTIC (LA) PROTOCOL

The protocol, described in [40], is designed for dynamic situations where no prior knowledge of the surveillance stations to be visited is required. In this protocol, monitoring units equipped with GPS regularly send out beacons indicating their position. The beacons serve two purposes: firstly, they transmit the sender's position, allowing the UAV to compute its route accordingly; secondly, they enhance security by providing additional information in case the UAV loses communication with the surveillance station's beacon message. The utilization of beacon messages in this protocol enables adaptability to change conditions, such as the movement of surveillance stations. The protocol allows for fine-grained patrol and surveillance to be assigned to surveillance stations, while coarse-grained patrol and surveillance are assigned to UAVs. Notably, the protocol does not require knowledge of the surveillance station positions prior to travel. When the UAV is powered up, it waits for beacon messages from surveillance stations to determine its initial visit location. In scenarios with multiple surveillance stations, the protocol employs a greedy method, selecting the surveillance station closest to its current location as the next visiting position on a hop-by-hop basis.

G. SecRIP: SECURE AND RELIABLE INTER-CLUSTER ROUTING PROTOCOL

The Secure and Reliable Inter-cluster Protocol (SecRIP) aims to enhance both the Quality of Service (QoS) and the Quality of Experience (QoE) metrics [41]. The protocol utilizes two methods, namely the chaotic algae method and the dragonfly method. They are used to manage cluster selection, maintenance, and information dissemination in inter-cluster communications. The design of this protocol is inspired by the activity of the natural ecosystem in our surroundings. The protocol consists of two stages, the first of which is cluster formation, followed by cluster head selection and safe and secure inter-cluster navigation. Initially, the system is clustered without separating any nodes, where each node within the network area becomes part of a cluster using the chaotic algae method. This system helps to efficiently manage the network and reduces latency in data transmission. In the second step, the dragonfly method is used to select the cluster head (CH), which facilitates effective message transmission within and among individual clusters. This method generates individuals using a successful approach and then combines them to construct an artificial biological entity. By combining the chaotic algae method and the dragonfly strategy, this protocol ensures connectivity and achieves secure and efficient data transmission while conserving energy. The complexity of the protocol during message sending depends on the density of the nodes and the number of accessible neighboring nodes. When the number of links between UAVs is at its maximum and each node is sending messages, the complexity of both methods is in the order of $O(ntlog(n))$.

H. GEOGRAPHIC MOBILITY PREDICTION ROUTING PROTOCOL

The focus of this study is on assessing the reliability and effectiveness of a network of unmanned aerial vehicles (UAVs) [42]. In the absence of messages to transmit, UAVs will fly quietly using a specific method. The endpoint's velocity and location are determined using a response-based approach. When a UAV needs to transmit a signal, it sends a message called a Neighbor Discovery (ND) signal. The environment responds with the required data, which is then saved in the sender's neighboring or surrounding database. Afterward, the transmitter remains silent as it calculates and selects the next hop. To avoid detection, the neighbors also remain silent. This differs from GPSR, which requires UAVs to transmit regularly. To accurately identify the destination or determine the next hop, the transmitter cannot receive sufficient data at once. Therefore, the forecasting approach is used to estimate the location and movement of neighbors and the target. This results in more accurate signal delivery compared to not considering movement. Greedy sending fails when a route is null. This protocol also enables border forwarding, which can reduce the likelihood of encountering a routing null by extending the transmission distance. A larger area is advantageous for locating an acceptable next hop and continuing greedy forwarding.

I. FOUNTAIN-CODE BASED GREEDY QUEUE AND POSITION ASSISTED ROUTING PROTOCOL (FGQPA)

This protocol, cited as [43], employs a Power Allocation and Routing (PAR) strategy to minimize network latency caused by line delay. The PAR strategy uses a "closest or nearest span" method to send messages to their targets with minimal delay. The protocol architecture aims to reduce system latency while ensuring secure data transmission among all parties. Rather than forwarding only one or a few flows, transporting entire flows to the appropriate next step is preferred. This protocol achieves this by having the entire stream of data pass through a node, which eliminates the need to manage separate lines for each flow of data, reducing the number of required lines to one. Each node handles a single physical queue for the entire network flow due to the protocol's unique features. Sharing span data and queue data across nearby nodes is a crucial aspect of the FGQPA design. Nodes can use the overhearing technique to listen to their environment and store the cost of gathering the necessary information. The FGQPA header, placed before a router or node transmits a signal, displays the node's essential data. The Type field identifies the various types of information messages that can be sent over the network, and the IP location field represents the current broadcasting node's IP location. The speed vector field indicates the transmitting node's current velocity or speed, and the location field presents the node's actual location. The line delay size field contains the queue size data piggybacked by the sending message. Each node in the system must have a local database to enable routing choice. The FGQPA header is also present in the beacon or *hello* packets. After T times of silence, a node sends a *hello* signal and begins the message transmission procedure.

J. GREEDY FORWARDING AND LIMITED FLOODING-BASED ROUTING PROTOCOL (PSO-GLFR)

This protocol is designed to function in a dynamic situation without requiring any data on the stations to be visited, which is the theme of the paper [44]. Monitoring units are assumed to have GPS and to regularly send out beacons indicating their position. The beacon plays two roles: first, it transmits the sender's position, allowing the UAV to calculate its route and fly accordingly; second, it adds an extra layer of security in case the UAV loses communication with the surveillance station's beacon message. Since adjacent surveillance stations cannot broadcast beacons at the same time and can also provide data on the position of surrounding stations, using beacon messages to facilitate UAV communication makes this protocol adaptable to changing conditions, such as when surveillance stations move. For instance, fine-grained patrol and surveillance can be assigned to surveillance stations, while coarse-grained patrol and surveillance can be assigned to UAVs. Before departure, this protocol does not require surveillance station position data. When the UAV is activated, it flies off and waits for beacon messages from surveillance stations to determine its first visit location. As there may be multiple surveillance stations in the area, this protocol uses the greedy method, which selects the closest surveillance station transmitting the beacon signal as the next visiting position on a hop-by-hop schedule.

K. LINK STABILITY ESTIMATION-BASED PREEMPTIVE ROUTING (LEPR) PROTOCOL

This paper proposes to use a connection stability measurement to calculate multiple stable link-disconnected routes and select a secure path to replace a failing connection in a short time [45]. The protocol calculates strong connections between disconnected nodes and establishes an extensive connection stability measurement that summarizes the link's past, present, and future states. The new measure includes three components: connection quality, security level, and mobility forecasting factor, each corresponding to a condition. Although it can provide an acceptable path to the target, it generates fewer alternative pathways, particularly in limited areas. To calculate multiple stable link-disconnected pathways between origin-targeted combinations, the Route Request and Route Reply messages are updated with two additional elements named metric and first hop. However, midway nodes cannot transmit an RREP directly to the sender to verify the discontinuous pathways' correctness. After receiving the RREP, an inferior node must take another backward path to the sender, and several resend periods must elapse before a connection is determined damaged, leading to significant overhead. Moreover, the principal route's failure due to node movement can affect other routes. The semi-proactive path monitoring procedure initiates a recovery process by seeking a better quality route to replace the primary path when it detects a connection in operation that is likely to fail. The alternative could be a route backup or the most recently discovered one during the path-searching process.

L. 3D CONE SHAPED LOCATION-AIDED ROUTING PROTOCOL

3D Cone Shaped Location-Aided Routing (3DC-LAR) protocol [46] shows that the design and length of the Request Zone can have a big impact on how much transportation cost is minimized in the network. This strategy presents a change from the conventional LAR because of the flying capability of drones, in which a 3-Dimensional cone-shaped Request Zone is utilized instead of the rectangular design or shape of the Request Zone. Several assumptions can be made about the exclusive characteristics of FANET. Each UAV node uses a GPS device to learn about its 3-Dimensional positional data, for example, (X_i, Y_i, Z_i), and data about its surroundings as well as a target drone. It then shares this important data via Signals and modifies the neighbor list database. The intelligent n number of drones are launched in random order and have a similar communication area. The connections between UAVs must be bidirectional. It is possible to compute whether or not adjacent UAVs are inside the shape of a 3-Dimensional cone. Suppose the 3-Dimensional cone's top is at UAV node U_S, with positions X_S, Y_S, Z_S as well as the sender drone be changed at U_S hub. R can be the cone's radius as well as the value of the position of the target UAV node U_D is X_D, Y_D, Z_D where R reflects the target UAV's communication area. The space or distance H between U_D and U_S, commonly known as the 3-Dimensional cone's height can be computed, and the cone design constant is computed here: $C = \frac{R^2}{H}$, where H is the distance between the source or sender UAV and Destination or target UAV, R is the transportation area and radius of three-dimensional cones. H can be obtained with the following equation:

$$H = \sqrt{(X_S - X_D)^2 + (Y_S - Y_D)^2 + (Z_S - Z_D)^2} \tag{3}$$

Whenever the Route Request is begun, the sender drone U_S can send the target drone's radius and the transmitting drone's position value X_S, Y_S, Z_S via the hello packet. Due to the Request Zone being inside the U_B, the drone U_B gets the Route Request from U_S, while another side U_A gets this query for onward communication due to this node being just within the Request Zone. This protocol uses a similar transmitting technique till the query arrives at the target drone U_D. When the Route Request packet arrives at U_D via the interior drones, the U_D sends the Route Reply to the U_S utilizing the unicasting mechanism. The path-searching procedure has been improved here.

M. FUTURE NETWORK TOPOLOGY-AWARE ROUTING (FNTAR) PROTOCOL

This paper focuses on utilizing the position and movement data of UAVs for a position-conscious routing method [47]. The method utilizes UAVs' locations, paths, and movement data to determine the upcoming locations of all UAVs in the system, allowing the protocol to pick the nearest node to the target later as the packet's relay node. The drone examines the network structure to identify the quickest route to the packet's target node, and if it cannot determine the quickest route, it computes all the upcoming locations of its extended surroundings after a specific period. The method can determine the upcoming possible latency of imaginary linkages between all the generalized neighbors and the target node, enabling it to select the node with the shortest upcoming possible latency after the period. If the drone's individual possible upcoming latency is smaller than its generalized surroundings' upcoming possible latency, it stores the signal, and the provisional target of the signal is selected among the generalized surroundings with the shortest upcoming possible latency. Signals can be rapidly sent to their ultimate target, typically a base station, using Dijkstra's method to find the quickest route. When a drone receives a packet from another node, a single-copy forwarding algorithm is performed, and if the number of surroundings of the sender drone is less than N times, the sender drone holds the signal after sending it to all of the surroundings until it meets the latest surrounding node.

N. MOBILITY PREDICTION AND DELAY PREDICTION ROUTING (OLSR PMD) PROTOCOL

This paper introduces a protocol designed to enhance networking connectivity in UAV systems by addressing the challenges posed by UAV node movement [48]. The protocol utilizes movement forecasting to predict the future location of drones, enabling the selection of reliable peers or surrounding nodes as MultiPoint Relays nodes. GPS technology is leveraged to determine the speed and location of drones, and the protocol utilizes *hello* packets for the exchange of location coordinates and speed among UAV nodes to assess adjacent node robustness. The movement prediction is performed using a self-adjusting Kalman filter model, which offers applicability in various domains such as photo analysis and object monitoring. The protocol incorporates a Dual Dijkstra method to compute the routing database, where the first stage identifies routes with the fewest steps and the second stage selects the route with the shortest latency, accounting for the expected queuing latency of nodes along the route. By minimizing end-to-end latency, this protocol aims to optimize communication in UAV networks, particularly in scenarios where multiple shortest routes exist between nodes with similar hop counts in an ad-hoc system.

O. ICRA: AN INTELLIGENT CLUSTERING ROUTING APPROACH FOR UAV AD HOC NETWORKS

In [75], the routing protocol considers the challenge of a rapidly changing environment and proposes an intelligent clustering routing approach (ICRA). ICRA consists of three key components: the clustering module, the clustering strategy adjustment module, and the routing module. The UAV ad hoc network considered in this approach includes UAV nodes (NU) and a ground station (GS), enabling communication between UAVs and between UAVs and the ground. Each UAV node possesses unique capabilities, resources, flight routes, and activities. Communication with the GS is possible when a UAV node is within its communication range, assuming all nodes have a GPS with a network time protocol system. The proposed scheme aims to cluster UAV nodes into groups using a clustering algorithm to establish the network topology. According to the article [28], the protocol follows a self-adapting clustering framework for maintaining a consistent network topology to ensure efficient routing.

P. AN ADAPTIVE-BASED PREDICTED NODES BEHAVIOR ALGORITHM IN FLYING AD HOC NETWORKS

The PF-WGTR routing algorithm, recommended in this study [76], incorporates various factors such as node speed, acceleration, flight direction, and link quality to assign weights to network nodes. These weights are then utilized to forecast future weights and determine the optimal course of action. The computation of weights takes into account node speed, direction, acceleration, and connection quality while utilizing the current position, velocity, and acceleration of nodes to estimate future weights. Simulation results demonstrate the superior performance of PF-WGTR compared to other protocols. As FANETs present unique challenges due to node mobility, future research efforts aim to develop efficient routing protocols that can adapt to diverse constraints and leverage UAV-assisted concepts to address these challenges.

Q. LOW-DELAY ROUTING SCHEME FOR UAV COMMUNICATIONS IN SMART CITIES

This study in [77] introduces an optimized routing scheme based on the Optimized Link State Routing (OLSR) protocol to address the low delay requirements in Flying Ad Hoc Networks (FANETs). The proposed scheme aims to reduce routing overhead caused by node relocation. Through simulations conducted using the NS3 network simulation environment, the performance of the original and enhanced versions of the OLSR algorithm is evaluated. The results demonstrate that the improved method outperforms the original approach in terms of usability and scalability, as indicated by metrics such as routing overhead, latency, and packet delivery rate. The study also highlights the limitations of conventional Mobile Ad Hoc Network (MANET) routing protocols for FANETs and emphasizes the potential of OLSR by incorporating link quality-based path selection. The simulations conducted using NS3 provide valuable insights into the enhanced OLSR routing protocol's performance metrics, including average end-to-end delay, packet delivery ratio, routing control overhead, and throughput. Overall, the proposed upgraded OLSR routing protocol shows promising results in addressing the challenges posed by high node speed and frequent routing updates in FANETs.

R. DESIGN AN ADAPTIVE TRAJECTORY TO SUPPORT UAV ASSISTED VANET NETWORKS

The research explores the utilization of unmanned aerial vehicles (UAVs) to enhance vehicular networks, specifically vehicular ad hoc networks (VANETs), which often face challenges such as frequent connection dropouts and degraded performance [78]. The proposed approach focuses on establishing an efficient communication channel between UAVs and VANETs to improve ground vehicle coverage, reduce packet loss, minimize delays, and prevent connection interruptions. Taking into account the limited power and connectivity capabilities of UAVs, the model leverages well-known traffic lanes and vehicle movements. The study investigates the potential of UAVs to strengthen VANETs by enhancing coverage, reducing delays, and mitigating connection issues. Through simulations, the proposed solution demonstrates improved throughput and reduced latency by establishing a communication channel between UAVs and VANETs. However, the article recommends further testing and exploration, particularly in complex road networks involving multiple UAVs, to achieve comprehensive coverage.

S. CROSS LAYER RESOURCE MANAGEMENT DYNAMIC SOURCE ROUTING (CLRM-DSR) PROTOCOL

The Cross-layer resource management dynamic source routing (CLRM-DSR) protocol is designed to improve the performance of the Dynamic Source Routing (DSR) method in Flying Ad Hoc Networks [79]. CLRM-DSR incorporates network quality evaluation and aims to reduce routing overhead. Unlike other protocols, it doesn't require regular broadcasting of routing data. However, DSR has limitations such as increased end-to-end latency due to route-finding procedures and lack of information about connection conditions at endpoints. The efficiency of FANETs using DSR becomes unpredictable when network architecture and connections change, affecting data packet delivery frequency. CLRM-DSR addresses these challenges by leveraging cross-layer resource control and connection quality indicators. The routing query signal in CLRM-DSR reduces routing costs, and when data communication is needed, a routing request is submitted instead of continuously transmitting routing data. The routing response is sent in unicast format, incorporating connection quality indicators to determine the best route. When data communication is required, the CLRM-DSR protocol submits an inquiry instead of continuously transmitting the routing data. Whenever any node requires transmitting information, the node checks to find out if the recipient node's routing details are present regionally or not. If yes, the node is able to transmit the data straight away, if not, it must transmit a routing request packet to carry out the procedure of route discovery in order to determine the best route to the final node. The middle node invokes the cross-layer resource control method to get the connection quality indicator $T_{i,*}$, whenever the final node gets a packet of navigating requests and delivers a route response signal in unicast format. After incorporating$T_{i,*}$, the quality of the connection area of the data packet will be substituted with the updated value. The node that was the source can get the connection performance indicator to different nodes $T_{i,*}$, whenever it gets the route reply message. The connection equivalent to the least $T_{i,*}$, acquired at the origin node is the one with the most reliable connection and is thus the best link for sending data since $T_{i,*}$, on the transmission channel is revised based on the connection's position.

T. MULTI-PATH WEIGHTED LOAD-BALANCING (MWL) ROUTING PROTOCOL

The routing protocol in [80] operates in two steps within the UAV-Net. In the initial phase, known as the route searching phase, Unmanned Aerial Vehicles (UAVs) in the network actively search for multiple node-disjoint paths leading to the Anchor UAV (AU) In the subsequent step, the UAVs transmit their data to the AU by distributing the weight over these paths. The primary objective is to find different node disjoint least hop routes from the UAV network nodes to the AU. The navigation method involves sending a route identification control signal from the origin node to the target node, which is transmitted throughout the network. The Anchor UAV selects the control packet with the least hops and checks for node disjoints. Each UAV maintains the navigation state data consisting of the route information between origin-destination pairs. This ensures robustness and reliability by finding different paths without common nodes. The navigation method involves transmitting a route identification control signal from the origin node to the AU through the network. The AU selects the signal with the fewest hops and checks for node disjoints. The resulting route data from the navigation state data is stored in each UAV. For data transmission, a weighted load balancing (WLB) technique is employed, distributing the data load across multiple paths to the destination. The WLB technique prioritizes lighter-weight paths to reduce congestion. In video transmission, the UAV-Net uses frames to carry the video feed, while the Multi-Path Weighted Load-balancing routing method adjusts the initial information rate during traffic congestion to maintain reliable transmission with minimal message loss.

U. SKELETON-BASED SWARM ROUTING (SSR) PROTOCOL

The routing technique in [81] establishes a leaf-like network structure, resembling a branching pipe, from the source to the destination. Nodes in the network dynamically adjust the data transmission quantity along these routes based on feedback received from potential senders. Each connection in the leaf structure is assigned a reward or cost, and the total reward is determined through a backward loop approach. The reward values are not pre-determined but are subject to change due to the dynamic nature of the swarm network. By utilizing ACK signals commonly used in routing methods, the total cost is distributed backward along the route. Each intermediate node in the mini-pipe to the destination initiates a local attempt to discover the current location of the destination if it anticipates the destination to be within its community based on its physical proximity. This is achieved by broadcasting an address request (AREQ) message containing relevant information such as the timestamp, destination identification, previous location, and initiator's location. Additionally, the routing technique incorporates the use of the Soft-max function with a temperature variable to select operations with higher probabilities, prioritizing more favorable actions. In cases of deliberate interruption or affected regions, skeleton-based swarm routing can be combined with identification strategies to reroute data away from the impacted areas.

V. SECURE ENERGY EFFICIENT DYNAMIC ROUTING PROTOCOL (SEEDRP)

The routing technique encompasses two phases: routing and security [82]. In the routing phase, a flexible routing method is employed to determine the most cost-effective path between the source and destination nodes. The primary objective of the security phase is to establish a Unique Dynamic Key to protect the transmitted information. The routing technique leverages cross-layer optimization with the Media Access Control (MAC) sub-layer to select suitable neighboring nodes for data transmission based on factors such as data transmission percentage, node velocity, and node inclination. The routing approach employs a multi-rate computation framework to facilitate communication between nodes in proximity. Using the cross-layer optimization approach, the transmitting node gathers information transmission percentages and communication distances from the MAC layer. The highest transmission percentage among the collected values is selected by the sending node. This information is included in the Route Request (RREQ) message, which is transmitted from the source node to its neighboring nodes. Each node in the network maintains a "Seen" database that contains tuples comprising the broadcast identity and origin location of each node. The "Seen" database is consulted to determine whether an incoming RREQ signal is a duplicate of a previously received one. If a matching record is found in the "Seen" database, the RREQ from the source node is discarded as a duplicate. If the received RREQ is not a duplicate and not intended for the receiving node or any other target node with a valid entry in the "Seen" database, the transmission of the RREQ is delayed. In most cases, separate transmitting nodes are selected, with the primary one being the source node initiating the communication and the potential relay node capable of forwarding the message to the destination. The successful broadcast ratio is calculated by dividing the total number of successful broadcasts by the total number of broadcasts transmitted in the network.

$$PDP = \frac{Number - of - effective - broadcasting}{Number - of - broadcasting} \quad (4)$$

Here, PDP refers to the probability of the Delivery of the package. To ensure the security of the transmitted data, the SEEDRP security method is employed. This method protects the information within the packets from unauthorized modifications by network attackers. During the encryption process, the Advanced Encryption Standard (AES) technique is utilized, providing robust data security. AES is known for its efficiency and speed compared to other encryption methods. It employs a unique dynamic digital password or key to effectively encrypt the data, safeguarding it from external surveillance and unauthorized access.

W. CROSS-LAYER AND ENERGY-AWARE AD-HOC ON-DEMAND DISTANCE VECTOR (CLEA-AODV) ROUTING PROTOCOL

The routing protocol described in [83] focuses on improving efficiency by considering both the information layer and the network layer. A cross-layer approach is employed, incorporating two key ideas. The first idea involves using Glow Swarm Optimization (GSO)-based Cluster Head selection to minimize energy consumption throughout the network. Additionally, priority-based Carrier-Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) broadcasts are utilized to establish a fast Medium Access Control (MAC) model. In the GSO technique, each glowworm is assigned a unique luciferin value and a neighborhood spectrum for making placement decisions. The luciferin rate of a glowworm is determined by its fitness parameter and position relative to other organisms. The luciferin value of a glowworm is updated using the equation:

$$K_i(t+1) = (1-\beta)K_i(t) + \Omega G(Z_i(t)) \quad (5)$$

In this equation, 'i' represents an individual glowworm, $K_i(t)$ denotes the luciferin factor for that glowworm, β is the decay factor (with values between 0 and 1), $Z_i(t)$ represents the fitness parameter at location 'i', and Ω represents the improvisation factor. When a UAV needs to transmit data outside the coverage area of the Ground Control Station, an ad hoc collaboration of UAVs is formed. Data is transmitted through a series of hops using intermediate UAVs until it reaches the remote destination. The UAV connected to the Ground Control Station declares itself as the head of the cluster and initiates the cluster formation with other UAVs. The remaining UAVs become participants and join the cluster. If no UAV is in direct contact with the Ground Control Station, a relay aircraft from a different cluster can be used to establish a connection. The head of the cluster is selected based on fitness level, with the highest fitness UAV becoming the focal point of the cluster. The topology discovery in the base network involves three components: hop-count, new-parent-id, and old-parent-id. Two nodes cannot coexist in a 2-hop area as nodes spread and change. Cooperative-MAC employs multiple lanes to differentiate between messages of different priorities. Messages are included in the header and placed in a slack queue until the time limit expires. To avoid a node delivering an urgent message to a sleeping parent, the initial urgent message is sent during a specified time, causing the node parents to switch to MAC upon receipt. In case of an incorrect alarm, a fire node transmits a FALSE-ALARM signal, allowing its one-hop peers to reset their MACs. The predecessors of the node switch their MAC to normal mode while traveling to the main network in urgent mode until 'n' loops after receiving. These techniques and mechanisms contribute to enhancing the efficiency and performance of the routing protocol, enabling effective communication in UAV networks.

X. DELAY AND LINK STABILITY AWARE (DLSA) ROUTING PROTOCOL

In [84], the protocol encompasses the cooperative transmission of information and emphasizes connection durability. The navigation process consists of multiple stages, starting with the initialization phase and progressing to the verification of information transmission from the origin to the destination. The system segmentation phase divides the network into aerial and ground ad hoc networks, ensuring separate operations. The cooperative form of interaction between the aerial and ground networks is established and assessed. Subsequently, a Red-Black (R-B) priority tree is constructed for each network (Aerial, Ground, and Neural), with the Cognitive link serving as a virtual layer. Node selection follows the priority tree, prioritizing nodes with higher importance. If the most important priority node is chosen, the process continues; otherwise, the selection of the highest priority node is restarted. After node selection, connection durability is maintained through the evaluation of connection stability. If the current connection durability level meets the specified threshold, direct transmission is employed. Otherwise, the connection durability measurement technique is utilized. This technique involves finding routes and identifying nodes with the highest durability measurement within the communication range using Route Request (RREQ) and Route Reply (RREP) processes. The channel with the highest durability metric is selected for cooperative information transmission. The process concludes when the transmitter and recipient, both in the ground and aerial networks, successfully communicate over the wireless network.

Y. GW-COOP (GRAY WOLF ALGORITHM USING COOPERATIVE DIVERSITY TECHNIQUE) ROUTING PROTOCOL

In [85], the protocol incorporates the Gray Wolf Optimizer (GWO) algorithm, which mimics the cooperative behavior and social structure of gray wolves in order to optimize the routing process. The GWO algorithm is adapted to meet the specific requirements of mobile nodes in the network. The concept of collaborative diversity is introduced, where two relays support each origin-to-target connection, enhancing the reliability and robustness of the routing. The network structure is formed by a variable number of devices and the arbitrary placement of moving nodes. The performance and location of each node are evaluated based on an objective function that calculates the fitness of each node. The three most effective nodes, including the source, R_1, and R_2, are given priority in a specific order if they meet certain criteria. If the criteria are not met and the maximum number of iterations is not reached, the search process is reset until the criteria are satisfied. The collaborative diversity mechanism only applies to the nodes involved in the routing path. The positions of the nodes and their proximity to the targets are recorded and updated for the next iteration. It is essential for the nodes assigned to the aircraft to be aware of their locations before establishing the routing path. Collaborative diversity comes into play during the navigation phase, where the source node transmits the data to the destination either directly or through relays. There are different approaches for data transmission, depending on whether it is critical data or regular data, which reflect the overall system efficiency. In the case of critical data activity alerts during the flight operation, a priority buffer is activated, and an immediate flight to the destination is initiated. In the direct mode, where the source node and the destination are within a single hop, data is transmitted directly from the source to the destination. When critical data is en-queued, the collaborative diversity mechanism is activated, and the remaining data transmission is handled by selecting one of the top relay routes, R_1 or R_2. Once the sender decides to deliver the data through immediate shipment or relay transmission to the destination, the collaboration process is concluded. The data is simultaneously transmitted from the source to R_1, R_2, and the final destination. The destination node receives the data delivered by R_1 and R_2. To handle multiple incoming messages at the destination, an Enhanced Signal Noise Ratio Combining (ESNRC) technique is employed to combine and select the signals based on their signal-to-noise ratios. The ESNRC method uses the average SNR instead of the immediate SNR, allowing it to reject identical signals coming from different streams and select the one with the highest SNR.

Z. ENERGY-AWARE AND PREDICTIVE FUZZY LOGIC-BASED ROUTING PROTOCOL

An Energy-Aware and Predictive Fuzzy Logic-Based Routing Protocol for UAV communication is presented in [86]. According to the article. the route plan consists of two stages, namely the route-finding procedure and the route maintenance procedure. In the route-finding procedure, when the origin node lacks a path to the destination node in its forwarding database, it initiates a route request (RREQ) signal to nearby nodes. The neighboring nodes rank themselves based on various factors, such as movement instructions, fuel remaining, connection quality, and node durability. By replaying the RREQ signal, the efficiency of the navigation protocol is improved, and the issue of transmission flood is avoided. Additionally, a fuzzy approach is employed during the pathway-choosing stage to identify paths that are more efficient, faster, and require fewer hops. During the route maintenance phase, two stages are involved: avoiding route breakdown and rebuilding lost routes. The primary goal of the first stage is to identify and resolve any paths that encounter obstacles to ensure uninterrupted information communication in the network. The subsequent stage aims to promptly identify and replace faulty routes to minimize delays in the information-sending system. To detect failed paths, the origin node regularly examines the paths in its navigation database by sending route confirmation signals to the destination node. If the signal reaches the destination node successfully, the route remains active and an acknowledgment (ACK) signal is sent back. However, if the ACK signal is rejected, indicating a failed path, a route error (RERR) signal is sent to the origin node. In such cases, the origin node repeats the route-finding procedure to establish a new path to the destination node.

III. PERFORMANCE METRICS

This section delves into the various performance metrics that have a significant influence on the effectiveness of routing protocols. The existing routing protocols are evaluated qualitatively and unfavorably based on the following parameters. Figure 2 provides an overview of the various parameters that are taken into account to evaluate the performance of UAVs. These parameters play a crucial role in the design of efficient routing protocols for UAV communication, and they need to be carefully considered to ensure optimal performance. Therefore, the parameters that are taken into consideration to assess the performance of the UAV routing protocol are defined and justified below.

A. MOBILITY

In the context of UAV routing protocols, mobility refers to a UAV's ability to move freely and easily from one location to another. This characteristic is essential to consider when designing and evaluating routing protocols since it directly impacts the performance of the network [49]. The efficiency of a routing protocol can be measured based on its ability to operate effectively in scenarios with high UAV mobility. When a routing protocol performs well in situations where UAVs are highly mobile, it is considered efficient [50]. This is because mobility can have a significant impact on the performance of a routing protocol, affecting its ability to maintain connectivity, transmit data, and avoid collisions with other UAVs and obstacles [51].

B. LATENCY

Latency is a term used to describe the time interval between the transmission of a data packet and its reception by the destination node [52]. In the context of routing protocols, low latency is an essential feature that contributes to efficient and effective data transmission. This is because high latency can result in delays, which can negatively impact the performance of the network [53]. As a critical performance metric, evaluating latency can help assess the efficiency of a routing protocol. A routing protocol that is designed to minimize latency is desirable because it can contribute to faster and more reliable data transmission [54]. In contrast, a protocol that has high latency can result in poor network performance, leading to issues such as dropped packets and reduced throughput [55]. Therefore, it is crucial to measure and optimize latency when designing and evaluating routing protocols for UAV networks.

C. QUALITY OF SERVICE (QoS)

The term Quality of Service (QoS) pertains to the approach employed to regulate the flow of data traffic across a system. QoS encompasses any technique that is implemented to manage the transfer of information, which aims to minimize the occurrence of message loss, delay, and jitters within the system, as cited in [56]. In essence, a routing protocol is regarded as efficient when it takes into account the QoS factor as an essential component.

D. ENERGY EFFICIENCY

Energy efficiency is the process of reducing energy wastage by utilizing less energy to accomplish the same amount of work. This feature is crucial for Unmanned Aerial Vehicles (UAVs) as they typically operate on a limited power supply [57]. Energy efficiency, in the context of UAVs, refers to the proportion of total energy input utilized for navigation, with minimal energy loss or wastage, as mentioned in [58]. When a routing protocol incorporates effective energy usage, it is deemed to be more efficient in terms of energy consumption.

E. END-TO-END DELAY

End-to-end delay is the duration required for a message to travel from the originating node to the receiving node across a network. This particular parameter is calculated to determine the efficacy of a routing protocol [59]. A consistent and stable end-to-end delay is considered a positive attribute of a routing protocol [60]. This means that the protocol is capable of delivering messages with minimal delays, ensuring a smooth and seamless communication flow between nodes in the network.

F. THROUGHPUT

Throughput is a performance metric that represents the total volume of data that is securely and effectively transmitted from one point to another [61]. This parameter is highly critical and significantly impacts routing protocols, as efficient communication requires a high level of throughput, as cited in [62], [63]. Conversely, routing protocols with low throughput are deemed to be less efficient, as they are unable to transmit data effectively.

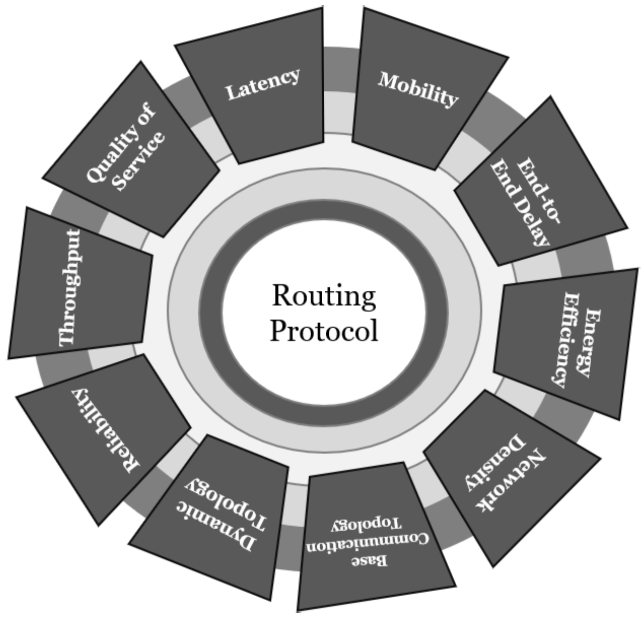

FIGURE 2. Performance metrics for the UAV routing protocol.

G. RELIABILITY

Reliability is a critical parameter that describes the ability to ensure that data transmitted from the sender node is accurately received by the destination node. A routing protocol for UAV communication can be deemed reliable if it can consistently ensure that data is transmitted accurately and without errors [64]. This parameter is essential in ensuring efficient data transfer in UAV communication since data accuracy and consistency are paramount for successful communication between nodes [65]. Therefore, a reliable routing protocol is crucial in ensuring the smooth flow of communication in UAV networks.

H. NETWORK DENSITY

Network density is a metric that refers to the percentage of possible connections in a network that are connected and functioning properly to enable efficient data transmission [66]. This parameter is vital and needs to be taken into account when evaluating the performance of UAV communication [67]. A routing protocol that can operate effectively in highly dense networks is considered a good routing protocol [68]. This means that the protocol can handle the increased traffic and data transfer demands in densely populated areas, which is essential for successful UAV communication in urban and crowded environments. Hence, network density is a crucial parameter that must be considered in assessing the performance of UAV routing protocols.

I. DYNAMIC TOPOLOGY

Dynamic topology is a term used to describe a network structure where connections are established autonomously between nodes, allowing for effective communication. This parameter is used to evaluate the efficiency of a routing protocol in UAV communication [69]. A routing protocol that takes into account the dynamic topology of a network is considered highly effective, as it can adapt to changes in the network structure and make optimal routing decisions based on the current topology [70]. This adaptability is crucial in UAV communication since the network topology can change rapidly due to the UAV's mobility and changing environmental conditions. Therefore, a routing protocol that can effectively handle dynamic topology is essential for efficient and reliable UAV communication [71].

J. BASE COMMUNICATION TECHNOLOGY

Base communication technology refers to the method that represents the node's navigation strategy with the ground station or base station [72]. This parameter is crucial in UAV communication and needs to be taken into account to achieve optimal performance [73], [74]. The choice of base communication technology can impact the efficiency and effectiveness of the routing protocol by affecting the quality of communication between nodes. The appropriate selection of the base communication technology can impact parameters such as throughput, end-to-end delay, and reliability. Hence, the base communication technology needs to be carefully chosen to design an efficient and effective routing protocol for UAV communication.

IV. PERFORMANCE ANALYSIS

In this section, a comprehensive summary and analysis of the existing routing protocols for UAVs is presented. Instead of a direct comparative analysis, the section provides an in-depth explanation and summarizing of the surveyed routing protocols. Thus, each protocol is evaluated using the parameter metrics introduced earlier in the article. The evaluation results are presented in Table 1, providing a concise overview of the protocols. Additionally, a focused discussion is provided for each specific protocol, highlighting their respective strengths and weaknesses. This analysis provides valuable insights into the effectiveness of different routing approaches in the context of UAV networks.

The BR-AODV routing protocol [32] demonstrates good performance in terms of low mobility, latency, and quality of service. It employs the Boids of Reynolds strategy as its base communication technology. However, energy efficiency and dynamic topology have not been taken into consideration.

The Reactive Greedy Reactive (RGR) routing protocol excels in mobility and latency but lacks consideration for quality of service, dynamic topology, reliability, and energy efficiency [36]. It performs well in end-to-end delay and throughput but may face challenges in highly dense networks. The protocol utilizes Mobility prediction technology as its base communication strategy.

When applied in navigation, the Smart IoT Control-Based Nature Inspired Energy Efficient Routing (eAntHocNet) protocol [37] showcases strong performance in latency, quality of service, energy efficiency, end-to-end delay, throughput, reliability, and dynamic topology. It utilizes the classical Ant Colony Meta-heuristics strategy as its base communication approach and considers network density.

The Jamming Resilient Multipath (JarmRout) routing protocol [38] efficiently handles latency and quality of service. However, it does not consider crucial factors such as energy efficiency and reliability. It performs well in low-mobility scenarios and applies to jams in base communication. It also evaluates end-to-end delay, throughput, and dynamic topology effectively.

The Course Aware Opportunistic Routing protocol [39] employs Wi-Fi as its base navigation method and performs well in latency, mobility, and end-to-end delay. However, it lacks evaluation in energy efficiency, quality of service, reliability, end-to-end delay, throughput, and network density. It excels in dynamic topology.

The Secure And Reliable Inter-cluster Routing protocol [41] exhibits strong performance in reliability, quality of service, energy efficiency, mobility, end-to-end delay, and throughput. However, it shows poor performance in latency. It utilizes clustering using the Algae strategy as its base navigation method and considers network density and dynamic topology.

The Geographic Mobility Prediction Routing protocol [42] employs two-hop neighbor selection in its base communication technology. It demonstrates good performance in reliability and dynamic topology while also considering reliability. However, it does not evaluate latency, energy efficiency, end-to-end delay, throughput, and quality of service. It performs well in high network-density scenarios.

The Fountain-Code Based Greedy Queue And Position Assisted Routing (FGQPA) protocol [43] utilizes the nearest span as its base navigation technology. It shows good performance in mobility and latency. It performs well in end-to-end delay and throughput but does not evaluate parameters such as efficiency, quality of service, reliability, and dynamic topology. It is suitable for highly dense networks.

The Greedy Forwarding and Limited Flooding Based Routing (PSO-GLFR) protocol [44] exhibits good performance in end-to-end delay, throughput, and reliability. It employs a flood routing strategy in its base communication but does not consider mobility and latency. Energy efficiency is taken into account, but network density and dynamic topology are not considered.

The Location Agnostic (LA) Routing protocol [40] considers parameters such as latency, energy efficiency, end-to-end delay, and throughput. It also evaluates reliability and network density. However, it does not perform well in terms of high mobility and quality of service. It utilizes a wireless network as its base navigation technology and incorporates dynamic topology.

The Link Stability Estimation-based Preemptive Routing (LEPR) protocol [45] excels in mobility and latency. It covers the quality of service and employs a wireless network as its base communication. However, energy efficiency is not considered. It evaluates end-to-end delay, throughput, network density, reliability, and dynamic topology effectively.

The 3D Cone Shaped Location-Aided Routing (LAR) protocol [46] primarily utilizes 3D cone-shaped request zones in its base communication technology. It performs well in mobility, latency, end-to-end delay, and throughput. However, it lacks consideration for parameters such as energy efficiency and quality of service. It is a less reliable protocol but demonstrates good performance in network density and dynamic topology.

The Future Network Topology-aware Routing (FNTAR) protocol [47], which employs future prediction technology in its base navigation, does not consider mobility and latency. It also lacks consideration for energy efficiency and quality of service. It is less reliable and may pose challenges in sending secure data packets. However, it performs well in end-to-end delay, throughput, network density, and dynamic topology.

Mobility Prediction and Delay Prediction Routing (OLSRPMD) protocol [48] shows good performance in end-to-end delay, throughput as well as dynamic topology. Moreover, the protocol performs well in latency or delay also. In this protocol, neighbor connection persistence is utilized as the base communication technology. However, this protocol may not perform efficiently in high mobility and in dense network. It is also observed that this routing method is less reliable in transmitting data packets. Quality of service, as well as energy efficiency, is also not considered in this routing protocol.

In the ICRA (Intelligent Clustering Routing Protocol) study, the protocol's performance was evaluated in three experimental scenarios, focusing on clustering efficiency, topology stability, energy efficiency, and quality of service. ICRA demonstrated faster clustering with improved efficiency and consistent topology stability across different scenarios. It also outperformed fixed-weight techniques in terms of energy efficiency and network longevity, thanks to its utility computation method [75].

The Adaptive-based Predicted Nodes Behavior Algorithm is another routing protocol that enables the establishment of stable routes, reduces data loss, and optimizes energy usage [76]. It considers factors such as node speed, variations in speed, and direction during the route selection process. Link quality is determined based on the speed and location of intermediate nodes, and future weights are calculated using predicted values for future node characteristics. This adaptive routing path selection process takes into account the present and future weights to choose the relay node, ensuring efficient routing in FANETs.

The Low-delay Routing Scheme for UAV Communications in Smart Cities proposes enhanced OLSR routing methods for FANETs, considering neighbor connectivity, power, and bandwidth. It introduces a neural network method for precise route computation and conducts simulations to evaluate its performance [77]. The simulations consider various network factors, and the results demonstrate improved services for FANET applications, decreased control message volume, and enhanced routing performance. The modified OLSR (MOLSR) protocol, incorporating connection stability and node bandwidth, outperforms OLSR in packet delivery rate, throughput, and stability.

In [78], the proposed system's success is validated through simulation results, which demonstrate reduced end-to-end delay and improved throughput compared to the baseline. The integration of UAVs into VANETs using DSRC units enhances message delivery and lowers latency. However, the study does not analyze potential drawbacks related to network density, topology, mobility, latency, quality of service, energy efficiency, and dependability. Further testing and investigation of complex road networks with multiple UAVs are recommended for comprehensive coverage.

The Cross-layer Resource Management Dynamic Source Routing (CLRM-DSR) protocol [79] exhibits good performance in terms of mobility and end-to-end delay. However, it does not consider factors such as latency, energy efficiency, quality of service, dynamic topology, and reliability. It performs well in terms of throughput but may not be suitable for highly dense networks.

The Multi-Path Weighted Load-balancing (MWL) routing protocol [80] utilizes the Weighted Load Balancing (WLB) mechanism as the base navigation method. While it considers parameters such as energy efficiency and quality of service, it does not account for reliability and network density. It performs well in dynamic topology, latency, end-to-end delay, and throughput but may not be suitable for high-mobility scenarios.

The Skeleton-based Swarm Routing (SSR) protocol [81] demonstrates better performance in routing due to the high mobility feature of Unmanned Aerial Vehicles. It performs well in scenarios involving latency, throughput, and dynamic topology. However, it does not consider parameters such as energy efficiency, quality of service, reliability, and end-to-end delay. It uses the classical Leaf-Like Routing Pipe technology as the base communication method and considers network density.

The Secure Energy Efficient Dynamic Routing Protocol (SEEDRP) efficiently executes quality of service (QoS), including latency [82]. It performs well in high mobility scenarios and considers network density. However, it does not account for parameters such as end-to-end delay and dynamic topology. It employs Cross-Layer Optimization in the base communication method and also considers energy efficiency, throughput, and reliability.

The Cross-Layer and Energy-Aware Ad-hoc On-demand Distance Vector (CLEA-AODV) routing protocol [83] demonstrates good performance in terms of latency, energy efficiency, end-to-end delay, and throughput when network density is considered. However, it has poor performance in mobility and reliability. It is less secure in terms of transmitting packets and does not consider the quality of service or dynamic topology. It employs the Hop Count strategy as the base navigation method.

TABLE 1. Performance overview of the existing routing protocols for UAVs.

	Parameter Matrics									
	Mobility	Latency	Quality of Service	Energy Efficiency	End-to-End Delay	Throughput	Reliability	Network Density	Dynamic Topology	Base Communication Technology
BR-AODV [32]	L	L	C	NC	H	H	H	H	N	Boids of Reynolds Strategy
RGR [36]	H	L	NC	NC	H	H	L	L	N	Mobility Prediction
eAntHocNet [37]	L	L	C	C	H	H	H	H	Y	Classical Ant Colony Meta-heuristics
JarmRout [38]	L	L	C	NC	H	H	L	H	Y	Jamming
CORF [39]	H	L	NC	NC	L	L	L	L	Y	IEEE 802.11 (MAC)
SecRIP [41]	H	L	C	C	H	H	H	H	Y	Algae Strategy
Geographic Mobility Prediction [42]	H	L	NC	NC	L	L	H	H	Y	Two-hop neighbor selection
FGQPA [43]	L	L	NC	NC	H	H	L	H	N	Nearest Span
PSO-GLFR [44]	L	L	NC	C	H	H	H	L	N	Flood Routing
LA [40]	L	H	NC	C	H	H	H	H	Y	IEEE 802.11
LEPR [45]	H	L	C	NC	H	H	H	H	Y	IEEE 802.11
3DC-LAR [46]	H	L	NC	NC	H	H	L	H	Y	3D Cone Shaped Request Zone
FNTAR [47]	L	L	NC	NC	H	H	L	H	Y	Future Prediction
OLSR PMD [48]	L	L	NC	NC	H	H	L	L	Y	Neighbor Connection Persistence
ICRA [75]	L	H	C	C	H	H	L	L	Y	IEEE 802.11 (MAC)
PF-WGTR [76]	H	L	NC	C	H	H	L	L	Y	IEEE 802.11
OLSR [77]	H	L	NC	NC	H	H	L	H	Y	MultiPoint Relays
Adaptive Trajectory [78]	H	L	NC	NC	L	H	L	L	Y	IEEE 802.11p (MAC)
CLRM-DSR [79]	H	H	NC	NC	H	H	L	L	N	MAC Scheduling Scheme
MWL [80]	L	L	C	C	H	H	L	L	Y	Weighted Load Balancing (WLB)
SSR [81]	H	L	NC	NC	L	H	L	H	Y	Leaf-Like Routing Pipe
SEEDRP [82]	H	L	C	C	L	H	H	H	N	Cross-Layer Optimization
CLEA-AODV [83]	L	L	NC	C	H	H	L	H	N	Hop Count
DLSA [84]	H	H	NC	NC	H	H	H	H	Y	Collaborative Data Forwarding
GW-COOP [85]	L	L	NC	NC	L	L	H	L	Y	Gray Wolf Hierarchy
Energy Aware Predictive Fuzzy [86]	L	L	C	C	H	H	H	H	Y	Score Calculation

H -> High; L -> Low; C -> Considered; NC -> Not considered; Y -> Yes; N -> No

The Delay and Link Stability Aware (DLSA) routing protocol [84] utilizes Collaborative (Two-Way) Data Forwarding as the base navigation technology. It shows excellent performance in mobility, end-to-end delay, and throughput, and takes dynamic topology into account. It also performs well in reliable data forwarding and in highly dense networks. However, it does not focus on energy efficiency and does not consider parameters such as latency and quality of service.

The GW-COOP (Gray Wolf Algorithm using Cooperative Diversity Technique) routing protocol [85] demonstrates improved performance and reliability in dynamic topology. It utilizes a Gray Wolf Hierarchy strategy for base communication, prioritizing latency and energy efficiency. However, it lacks consideration for mobility, network density, quality of service, end-to-end delay, and throughput.

The Energy-Aware and Predictive Fuzzy Logic-Based Routing protocol performs well in latency, end-to-end delay, and throughput [86]. This navigation method is efficient enough in terms of energy use. After that, quality of service, as well as dynamic topology, has been also considered for routing. The protocol transmits data securely which makes the method reliable. Moreover, this routing method can perform proficiently in a highly dense network. The score Calculation technique is employed as the base communication technique in this protocol. However, the protocol fails to consider nodes' mobility for route selection purpose.

V. OPEN RESEARCH AREAS

Routing protocols for Unmanned Aerial Vehicles (UAVs) play a crucial role in achieving specific architectural objectives, such as enhancing network stability, prolonging UAV node lifespan, improving energy efficiency, minimizing delivery delay, and reducing routing complexity. However, the unique characteristics of UAV networks, including high mobility, expansive deployment areas, and extended service periods, present significant challenges for networking compared to traditional mobile networks. Additionally, optimizing outdoor routes for UAVs necessitates accounting for stochastic ambient states. Therefore, this section aims to identify and discuss a range of open research areas and design challenges pertaining to routing protocols in UAVs.

A. SECURE ROUTING AND INTRUSION DETECTION

The security of FANET nodes and their transmissions is a significant concern due to various threats such as external attacks, flooding, fraudulent data, and manipulation. To address these threats, several security mechanisms can be employed, including cryptography, link identification, proof of identity, and authentication streaming. In the context of exchanging sensitive information and imagery between aerial monitoring systems, enhanced protection measures are required. Traditional PKI-based asymmetric security solutions may not be suitable for structure-less UAV networks due to the absence of a central entity for issuing digital signatures. In such cases, hardware-driven security keys can be utilized to enable non-repudiation. Furthermore, alternative localization methods can be employed to mitigate the impact of jamming attacks on GPS positioning, and secure handover mechanisms can be designed. To ensure secure data transmission, the development of secure routing schemes is essential, taking into consideration the detection and avoidance of malicious nodes through behavioral mechanisms.

B. DATA-CENTRIC ROUTING

Data-centric routing protocols have the potential to enhance communication efficiency and reliability in FANETs by prioritizing content rather than the host. These protocols focus on disseminating data based on its importance, service requirements, and performance constraints, which are critical in UAV applications. For instance, in a group of UAVs communicating with a ground station and among themselves, the ground station expects data from a particular UAV to ensure the effectiveness and timeliness of transmission, rather than from any specific node that covers the area of interest. However, such data types have different service requirements and performance constraints and can be affected by the dynamic nature of UAV operations, such as high mobility, joining and leaving of FANET nodes, and varying network topology. As a result, the host-centric routing would be inadequate, and a paradigm shift is necessary towards data-centric routing protocols that prioritize information over the host for FANET applications. Such data-sharing mechanisms are also common in other ad hoc networks. FANET routing protocols must accommodate the service quality demands of UAV networks, such as delay, bandwidth, jitter, and packet loss, by considering traffic characteristics and network resources.

C. ENERGY EFFICIENT ROUTING

Efficient utilization of energy resources is a critical aspect of Unmanned Aerial Vehicles (UAVs) due to their limited battery capacity. Designing energy-efficient algorithms is essential to extend the battery life while maintaining optimal performance. The limited battery capacity of UAVs poses a significant challenge, as energy consumption is directly proportional to the level of data transmission. Therefore, to develop energy-efficient routing protocols for UAVs, it is essential to consider data transmission consistency, which means that data should be transmitted only when necessary. To achieve this, routing protocols should transmit data only to the UAV closest to the area of interest rather than consistently transmitting data to all UAVs in the network. Transmitting data to all UAVs is highly ineffective and could result in energy consumption that is not required. Additionally, deploying unplanned UAVs can lead to unnecessary data transmission and energy consumption. Therefore, designing routing protocols that can support limited yet effective data transmission can significantly improve the energy efficiency of UAVs. Energy-efficient routing protocols can be achieved by incorporating various factors, including the movement patterns of UAVs, the location of ground nodes, and the available bandwidth. A routing protocol that considers these factors can intelligently route data to the most energy-efficient path while ensuring data transmission only when necessary. Another approach to achieving energy-efficient routing is by using adaptive data transmission mechanisms. This approach involves varying the transmission power and data rate of UAVs based on the network conditions.

D. REGULATION AWARE NETWORK MODEL

The movement of objects in the airspace is governed by numerous regulations and guidelines, which include restrictions and designated areas for UAV flights. Many countries have created notification systems to mark off certain areas of airspace, where restrictions are in place for all types of UAVs. These areas are typically classified as Prohibited Areas, Restricted Areas, or Military Zones. Additional airspace may have temporary restrictions imposed during specific times, either for pre-planned events or in response to unforeseen circumstances, such as emergency incidents or flying near airfields or airports designated as "protected aerodromes," which are subject to tight restrictions. UAVs of any size are prohibited from flying within the Flight Restriction Zone (FRZ) of a protected aerodrome without proper authorization. Information about restricted or controlled airspace serves as input data and is used as a constraint in UAV route planning. Although air traffic control plays a significant role in designing and implementing UAV routes, none of the current routing methods for UAV networks have accounted for the complex nature of these regulations. It is also important to keep in mind that although some areas allow the use of UAVs, there may be restrictions on the altitude that a UAV can reach, especially in areas near airports, to prevent collisions with airplanes or helicopters. Failure to comply with these regulations could result in fines or even criminal charges. Therefore, it is crucial to incorporate these regulations into UAV network models to ensure safe and legal operations.

E. DYNAMIC ROUTE SELECTION

UAV routing faces the challenge of optimizing path selection and flight duration while ensuring accurate information transmission across the FANET nodes. The dynamic route selection mechanism in a routing protocol addresses this challenge by enabling rapid path selection and adapting the network topology to changing network conditions. By dynamically selecting and updating routes based on metrics such as link quality or traffic congestion, the mechanism minimizes energy consumption and end-to-end latency while ensuring efficient and reliable data transmission. Additionally, uploading a specific amount of data to an in-flight UAV while using limited energy for information transmission from sensors to UAV nodes requires careful consideration. Unlike two-dimensional wireless sensor networks that focus on sensor information-gathering tasks, UAV networking pathways are three-dimensional, requiring further research to identify the destination node and achieve optimal movement and path planning.

F. COLLISION AWARENESS

The integration of Unmanned Aerial Vehicles (UAVs) with Wireless Sensor Networks (WSNs) holds great potential for enhancing information collection efficiency, and fault tolerance and reducing end-to-end delay. However, due to the limited flight time and potential obstacles, practical collision avoidance and UAV management in such networks are becoming increasingly challenging. To address this, the adaptation of the Store-Carry-Forward (SCF) mechanism can be useful as it enables latency-tolerant transmission and is a reliable mechanism for message delivery in disrupted environments. Additionally, the UAV nodes must periodically broadcast their position and other relevant information to ensure proper coordination and prevent collisions. This information can be used to dynamically adjust the UAVs' trajectories to avoid obstacles and optimize data collection. Moreover, advanced algorithms such as machine learning can be used to predict the movements of UAVs and obstacles in real time, enabling more efficient and safe coordination.

G. SIMULATION TOOLS WITH UAV MOBILITY MODEL

According to the findings of the study, the absence of appropriate simulation tools for FANETs is a significant obstacle to progress in research in this field, resulting in a shortage of real-world modeling and simulation tests. Simulation tools are software applications or platforms that simulate real-world scenarios, while mobility models are algorithms that represent the movement patterns of mobile nodes. In the context of FANETs, simulation tools, and mobility models are critical for developing and testing various network protocols, communication techniques, and routing strategies. The lack of simulation tools that can accurately model FANET conditions presents a significant challenge in this area of research. Therefore, researchers must either improve existing simulation tools, such as NS-2, Opnet, and OMNeT, or develop new ones that cater specifically to FANETs. Furthermore, mobility models are crucial in simulating the movement patterns of UAVs in a FANET scenario. Mobility models can provide researchers with insights into how UAVs move and interact with each other in a particular environment, enabling them to develop more effective routing and communication strategies. The ultimate goal is to create a real FANET with actual UAVs using the suggested protocols, which will identify more practical requirements than theoretical or ideal processes that have not yet been discovered.

H. COGNITIVE RADIO (CR) ENABLED PROTOCOL

The utilization of cognitive radio technology in UAVs presents several significant challenges. Efficient and reliable spectrum sensing is crucial for identifying available frequency bands for communication, while effective spectrum management is essential for optimizing system performance. Integrating cognitive radio-enabled UAVs with existing wireless networks and infrastructure poses additional challenges due to differences in communication protocols and technologies. Seamless integration necessitates the development of new protocols and techniques to facilitate communication between UAVs and other wireless devices. Managing both primary and secondary users is essential to prevent interference with other users sharing the same frequency band. Designing algorithms that effectively handle interference and maximize spectrum utilization is a complex task. Extensive research is needed to develop robust and reliable algorithms for spectrum management, interference avoidance, and seamless integration with existing wireless networks.

VI. CONCLUSION

This survey article provides a comprehensive exploration of routing protocols in Unmanned Aerial Vehicular Networks (UAVNs). It examines several recently developed routing protocols in UAV communication, detailing their construction methods. The article also introduces performance metrics to analyze the efficiency of these protocols, considering the challenges faced by UAVs such as high mobility, dynamic topology changes, intermittent links, power constraints, and changing link quality. While the reviewed protocols address various aspects of designing routing protocols for UAV communication, there are still areas that require further attention. This article discusses open research areas, including regulation-aware network modeling, secure routing, intrusion detection with dynamic route selection mechanisms, and data-centric approaches with energy efficiency and collision awareness. The findings contribute to a better understanding of UAV routing protocols and highlight avenues for future research in this field.

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