Vietnam Journal of Science and Technology ***64***(1) (2026) 1–19
DOI: https://doi.org/10.15625/2525-2518/19637

REVIEW PAPER

Routing protocols for efficient communication in UAVNETs: A comprehensive review and analysis

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Received: 11 December 2023; Accepted for publication: 02 February 2024

Abstract. The efficient communication among Unmanned Aerial Vehicles (UAVs) has become crucial due to their rapid development and expanding use in various applications. Unmanned Aerial Vehicle Networks (UAVNETs) are increasingly recognized as an effective way of facilitating cooperative and coordinated operations among UAVs. Nevertheless, the distinctive attributes of UAVs, including their mobility, constrained energy resources and dynamic network topology, present major challenges when it comes to designing efficient routing protocols. This research paper provides a thorough review of routing protocols that are specifically designed for UAVNETs. The objective of this study is to present a comprehensive analysis of the current routing protocols, highlighting their main characteristics and the specific issues they aim to resolve.

Keywords: UAVNETs, MANETs, VANETs, routing protocols.

Classification numbers: 4.5.2, 4.9.1.

1. INTRODUCTION

Unmanned Aerial Vehicle Networks (UAVNETs) are poised to significantly influence human activities [1-3]. These networks consist of UAVs that operate remotely without pilots and can perform more complex tasks than standalone UAVs or typical MANETs. UAV applications span military and civilian domains, including disaster response and public safety [4], surveillance [5], border monitoring [6], autonomous observation [7], and wildfire management [8].

Due to UAVs' high mobility and dynamic behaviour, routing in UAVNETs is particularly challenging, requiring real-time decision-making. This has led to the development of routing protocols tailored specifically for UAVNET environments [9-12].

There are numerous studies on communication between nodes in an Ad-hoc network. Some well-known routing protocols were created for MANETs [13-15] and while they can be used for UAVNETs, it is possible that their performance is insufficient because MANET is a network with similarities to UAVNET but significant differences [16-20]. These differences are detailed below:

1. Mobility: MANET nodes have low mobility, whereas UAVNET drones are continuously in motion.

2. Changes in Network Topology: In contrast to UAVNET, the topology of a MANET network alters slowly and gradually.

3. Network node density (number of devices per monitored area): It refers to the number of devices covering a monitored area. UAVNETs generally have low density due to high mobility and the ability of each UAV to monitor a wide area.

Table 1 highlights key differences between UAVNET, MANET, and VANET, showing that UAVNET nodes have higher mobility, greater energy use, and more frequently changing topologies compared to the other networks.

Table 1. Comparative analysis of the characteristics of UAVNET, MANET, and VANET

Characteristics	UAVNET	MANET	VANET
Mobility	Fastest (100 m/s)	Slow (2 m/s)	Faster than MANET (20-30 m/s)
Network node density	Least	Low	Higher
Changes in topology	Frequently	Very less	Traffic dependent
Energy consumption	High	Moderate	Low
Transmission range	Large coverage	Small coverage	Small coverage

This paper analyzes and evaluates UAVNET routing protocols by examining their performance, strengths, and limitations across different scenarios, while identifying key challenges and future research directions. It addresses fundamental aspects of UAVNETs, including their distinction from other ad-hoc networks, functional roles, routing requirements, mobility models, and the role of artificial intelligence. The study also presents a comprehensive taxonomy of UAVNET routing protocols and highlights unresolved research issues.

The paper is organized as follows: Section 2 analyzes UAVNET routing protocols and their characteristics, Section 3 provides a comparative evaluation, Section 4 discusses routing challenges, and Section 5 concludes the paper.

2. ROUTING PROTOCOL IN UAVNETs

Routing protocols play a crucial role in facilitating efficient communication and data transmission within UAVNETs, which includes interconnected drones and potentially ground stations. These protocols are responsible for determining the procedure by which data packets are directed within a network, taking into account various factors such as network topology, node mobility, along with link quality. In UAVNET, there exist multiple routing protocols that are usually used. The subsequent subsections will provide a detailed examination of each category, as illustrated in Figure 1.

2.1. Proactive routing protocol

Table-driven is another name for the proactive routing protocol. In such a routing protocol, each node keeps a table that shows the full structure of the network. Due to the proactive feature of this routing protocol, routes are promptly accessible upon demand. However, the network incurs greater overhead costs due to the necessity of maintaining up-to-date information. Additionally, the network's throughput may be impacted as control messages are transmitted even during periods of no data traffic. Due to these circumstances, it can be concluded that proactive routing protocols exhibit limited effectiveness when deployed in extensive and dynamically mobile UAVNETs. This category encompasses a variety of routing protocols [21].

2.1.1. Optimized Link State Routing (OLSR)

OLSR [22, 23] protocol is a flat, proactive routing approach that operates without centralized control and continuously maintains updated routing tables, enabling rapid route discovery to all destinations. It uses HELLO messages to maintain neighbor connectivity and select Multi-Point Relays (MPRs), Topology Control (TC) messages to disseminate link-state information, and Multiple Interface Declaration (MID) messages to manage nodes with multiple interfaces. By employing MPRs, OLSR reduces control message overhead and improves routing efficiency and latency in UAVNETs. However, its reliance on periodic topology updates increases bandwidth consumption, and the computation of optimal paths requires considerable processing and storage resources.

2.1.2. Destination-Sequenced Distance Vector (DSDV)

DSDV protocol [24-26] requires each UAV to maintain complete knowledge of all other nodes in the network by regularly broadcasting routing tables to neighboring nodes, either incrementally or through full dumps, in order to keep network information up to date. This approach ensures loop-free routes to all destinations and enables the selection of optimal paths based on average settling delay, allowing routes to be available without setup delay. As a result, the protocol is easy to implement and continuously maintains updated routing information, ensuring reliable communication. However, even when the network is inactive, periodic table exchanges are required, leading to increased storage demands, unnecessary broadcasts, and additional consumption of bandwidth and battery power, which contribute to higher routing overhead.

Table 2 compares performance metrics of proactive routing protocols. OLSR performs well in high-mobility scenarios, offering high packet delivery, low latency, and high throughput, ensuring reliable UAV communication.

Table 2. Comparison of parameters used to evaluate proactive routing protocols

References	Protocols	Energy efficient	Throughput	End-to-End delay	Packet delivery ratio
[22, 23]	OLSR	×	✓	✓	✓
[24, 25]	DSDV	×	✓	✓	✓

2.2. Reactive routing protocol

The reactive or on-demand routing protocol [27] dynamically establishes routes only when required. When a source UAV needs to transmit data, it broadcasts a RouteRequest (RREQ) message using flooding, allowing each UAV to determine the best path to the destination. Once the destination is reached, it responds with a RouteReply (RREP) sent via unicast back to the source. This approach reduces unnecessary routing overhead compared to proactive protocols and forms the basis for many on-demand UAVNET routing schemes.

2.2.1. Dynamic Source Routing (DSR)

DSR protocol [28] begins when the source UAV sends a RouteRequest (RREQ) message to its neighboring nodes, using a unique request ID to avoid confusion from multiple responses.

Multiple RouteReply (RREP) messages may be received along the discovered path, and if changes in network topology make an existing route unusable, the protocol initiates route repair. Studies have demonstrated that DSR can successfully identify unique routes within UAV networks, ensuring reliable communication [29]. Due to these characteristics, the DSR is more suitable than proactive techniques in UAV environments with high mobility and unstable topologies, where repeatedly performing route discovery before each packet transmission, as in proactive approaches, becomes inefficient.

2.2.2. Ad Hoc On-Demand Distance Vector (AODV)

AODV [30] is a reactive routing protocol that establishes routes only when required, using RouteRequest (RREQ), RouteReply (RREP), and RouteError (RERR) messages to discover and maintain paths. Loop-free routing is ensured through the use of sequence numbers, while route expiration times help maintain freshness, and intermediate UAVs update their routing tables as needed. Owing to its on-demand nature, AODV is widely used due to its low processing and memory overhead and its ability to efficiently discover routes between specific source–destination pairs while minimizing control message overhead. However, dynamic route discovery can introduce latency, and frequent link failures, degraded route quality, and network congestion in highly dynamic UAVNETs may increase route rediscovery delays.

Table 3 compares reactive routing protocols, showing AODV performs well in high-mobility scenarios with high packet delivery, low end-to-end delay, and high throughput, ensuring reliable UAV communication in dynamic aerial environments.

Table 3. Comparison of parameters used to evaluate proactive routing protocols

References	Protocols	Energy efficient	Throughput	End-to-End delay	Packet delivery ratio
[28]	DSR	×	✓	✓	✓
[30]	AODV	×	✓	✓	✓

2.3. Hybrid routing protocol

Hybrid routing protocols address the high overhead of proactive and reactive approaches. While reactive protocols have longer route discovery times, proactive ones generate more control messages. These hybrid protocols [31] suit large, frequently partitioned networks

2.3.1. Zone Routing Protocol (ZRP)

In accordance with its name, ZRP [32] relies on the concept of zones. There are different zones for each node. Zones are defined as groups of nodes. In intra-zone routing, ZRP is used for routing within a zone. Sources and destinations can initiate data communication instantly if they are located in the same zone. ZRP is used for inter-zone routing, which involves sending data packets outside the zone. The protocol enhances the efficiency of global route queries and feedback, improving reliability in UAVNET communication; however, its performance is highly dependent on the selected zone radius, which is a critical limitation.

2.3.2. Temporally Ordered Routing Algorithm (TORA)

TORA routing protocol is distributed in nature that demonstrates efficiency, adaptability and scalability, operating on the principle of link reversal [33]. The TORA has been suggested as a potential solution for the efficient operation of wireless networks that are characterized by high mobility and multiple hops. The routing protocol is an on- demand protocol that initiates from the source node. The algorithm is capable of identifying multiple routes connecting a source (S) node plus a destination (D) node. Control messages are only sent to a select group of nodes nearby the site of a topological change, which is a crucial characteristic of TORA. To achieve this objective, the nodes retain routing information pertaining to neighboring nodes. The protocol determines loop-free and multiple routes between source and destination nodes; however, it may sometimes produce inconsistent valid results, which can affect routing reliability.

Table 4 displays a comparison of parameters employed to assess the effectiveness of hybrid routing protocols. The TORA exhibits poor performance in scenarios with a high degree of mobility. The TORA has a lowered packet delivery ratio, higher end-to-end delay, and decreased throughput. Ensuring an ideal balance of these factors is crucial for the establishment of protocols that can effectively and reliably facilitate data transmission and communication.

Table 4. Comparison of parameters used to evaluate proactive routing protocols.

References	Protocols	Energy efficient	Throughput	End-to-End delay	Packet delivery ratio
[32]	ZRP	×	✓	✓	✓
[33]	TORA	×	✓	✓	✓

2.4. Position-based routing protocol

PBRP [34] is a position-based routing protocol that selects forwarding paths using the geographical coordinates of nodes, obtained through GPS or other localization techniques. When a UAV needs to transmit data, it identifies the destination's location and forwards packets to neighboring nodes that are geographically closer to the target. This process continues hop by hop until the data reaches the destination. By relying on location information rather than complete routing tables, the PBRP improves scalability and efficiency, making it particularly suitable for highly dynamic and mobile UAV networks.

2.4.1. UAV-Assisted VANET Routing Protocol (UVAR)

UVAR [35] is a position-based routing protocol as it uses geographic location information of vehicles and UAVs to make routing decisions. In this protocol, each vehicle and UAV is given a unique ID and a geographic location using GPS or other location- sensing technologies. The information on the location is used to calculate the distance between nodes. It helps to determine the best route for transmission. It uses a combination of distance-based and direction-based routing to make routing decisions. It uses a technique called zone-based routing in which the network is partitioned into distinct zones in which each node is assigned to a UAV. The protocol reduces routing overhead and communication delay by relying solely on location information for routing decisions and offers improved scalability by partitioning the network into smaller, independently managed zones. However, the use of the carry-and-move-forward mechanism can introduce additional delays.

2.4.2. Connected-Based Traffic Density Aware Routing Protocol (CRUV)

In [36], the authors proposed a routing protocol for VANETs that employs UAVs communicating cooperatively as well as collaboratively. The CRUV uses the concept of traffic density to make routing decisions that enhance performance. In this protocol, location information, speed and direction of each vehicle are transferred to adjacent vehicles within its transmission range. Based on this information, the protocol calculates the traffic density in each network zone. The traffic density is estimated by calculating the number of vehicles in a particular zone and their average speed. Then, the CRUV decides to avoid congested zones and select the least congested path for packet transmission. The routing strategy utilizes a hybrid methodology that combines distance-based and traffic-density-based methods of routing to determine the most optimal routing selections. The routing protocol was designed to improve the efficiency and reliability of VANETs by reducing communication delays and increasing network throughput. However, it does not account for real-time distribution and delivery latency, which limits its effectiveness in time-critical scenarios.

2.4.3. Location-Aware Routing for Opportunistic Delay-Tolerant Networks (LAROD)

LAROD [37] is a proactive-based routing protocol (PBRP) that was developed particularly for delay-tolerant networks (DTNs) [38]. The Delay-Tolerant Networking (DTN) protocol has been specifically developed to ensure efficient operation in challenging environments and over extensive distances, such as those encountered in space communications. The LAROD facilitates the transmission of location information to neighboring nodes within its designated range. It then calculates the distance and direction of other nodes and selects the transmission route with the shortest distance. The LAROD routing utilizes a location prediction mechanism to anticipate the future positions of nodes through the analysis of previous patterns. The routing protocol utilizes a machine learning algorithm to gather knowledge about the movement patterns of the nodes and subsequently minimize communication latencies. The protocol effectively reduces communication delays and improves packet delivery ratio in DTNs; however, its reliance on the store-and-forward mechanism increases transmission latency and overhead.

2.4.4. GPSR-Adaptive Beacon and Position Prediction (GPSR-ABPP)

GPSR-ABPP [39] is a non-DTN single-path protocol. The proposed approach is a modification of the Greedy Perimeter Stainless Routing (GPSR) [40], incorporating adaptive beacons along with position prediction mechanisms in order to enhance both efficiency and reliability. Each node broadcasts location information using adaptive beacons that are transmitted at variable intervals based on its mobility and communication patterns. The adaptive beacons reduce the routing overhead. To forecast the future position of a node, the prediction mechanisms consist of machine learning algorithms (linear regression) that analyse the node’s movement patterns and communication history. It contains information about the locations of neighboring nodes, similar to GSPR. The protocol improves routing efficiency and reliability while reducing communication delays; however, its machine learning–based approach may suffer from low localization accuracy in more complex scenarios.

2.4.5. Robust and Reliable Predictive Routing (RRPR)

RRPR [41] aims to improve efficiency and reliability. The protocol includes the collection of data regarding the geographical positioning and density of neighboring nodes contained in the neighbor table that each node maintains. The prediction mechanisms are machine learning algorithms that study the node’s movement patterns and communication history to estimate its future location. The RRPR uses a robustness mechanism that ensures that the protocol can handle the unpredictable nature of wireless communication. This protocol uses multiple paths to transmit data. This mechanism provides a backup path for each primary path, which can be used in times of failure or congestion. The routing protocol enhances the efficiency and reliability of UAVNETs and increases the success rate of route establishment. However, a key limitation of RRPR is the difficulty in accurately measuring node angles, which can affect routing performance.

2.4.6. Distance-Based Greedy Routing (DSGR)

DSGR [42] is a PBRP that can transmit data packets between wireless networks efficiently. This protocol relies primarily on the physical location of network devices, as opposed to traditional IP addresses. Each network node in this protocol maintains a local map of the network's topology. The node closest to the destination (D) is selected to transmit data packets to the nearby node that is also closest to the destination. The protocol employs a fully distributed algorithm that incorporates predicted node locations, allowing it to outperform centralized shortest-path approaches. However, it does not account for how uncertainty in location prediction affects the optimality of the selected routing path.

2.4.7. Reactive Greedy Reactive Protocol (RGR)

RGR [43] is another PBRP that can transmit data packets between wireless networks efficiently. Similar to DSGR, it also uses the physical location of network nodes to determine the next step location, rather than traditional IP addresses. Each network node stores only location information and not the entire network topology. To transmit a data packet to a destination using RGR, the discovery phase is initiated in order to locate the path to the destination node. This approach is reactive, as the node only searches for the route when it needs to transmit. The protocol is more scalable than DSGR, as it maintains information only about neighboring nodes, and it can handle dynamic network topology changes through its reactive approach. However, the protocol does not address the differences between the two scoped flooding techniques.

2.4.8. Location-AIDED Delay Tolerant Routing (LADTR)

LADTR [44] is a PBRP designed for Delay Tolerant Networks. The LADTR protocol uses the physical location of the nodes for transmission, even when there is no direct communication path. The LADTR framework partitions networks into distinct regions, wherein each region includes a collection of nodes capable of intercommunication. Nodes within a given region participate in communication by means of direct packet exchange. However, in the scenario where it is necessary to transmit the data to a distinct geographical area, it employs a store-carry-forward mechanism to forward it through intermediary nodes. The protocol ensures a consistently high contact rate between UAV nodes, promoting a high packet delivery ratio while transmitting only a single instance of data to avoid message duplication. However, the stability of its location estimation system could be improved by optimizing the Gauss-Markov and semi-Markov process model parameters.

We have examined the advantages and limitations of each protocol. Table 5 presents a comparison of parameters used to measure the performance of the position-based routing protocols mentioned above. It is evident from the data in this table that, despite the fact that these protocols are developed for UAVNETs, they place varying performance parameters in order to accommodate diverse application scenarios and fulfil unique requirements. End-to-end delay reduction through network topology adjustments is a characteristic shared by all the works in [35, 36, 39, 42-44]. However, in [35], the protocol offers improved scalability by facilitating the division of the network into smaller parts that may be managed separately. In the study referenced in [36], a routing protocol was particularly designed to improve the efficiency and reliability of VANETs. The protocol in [39] reduces delay in communication, improves efficiency, and increases dependability. It outperforms the centralised shortest algorithm due to the fact that the algorithm utilised in [42] is fully distributed and incorporates predicted locations. The protocol in [43] accommodates dynamic changes in the topology of networks by employing a reactive approach. The protocol in [44] guarantees a continually high level of contact between UAV nodes, hence increasing the packet delivery ratio.

Table 5. Comparison of parameters used to evaluate proactive routing protocols.

References	Protocols	Packet delivery ratio	Throughput	Overhead	End-to-End delay
[35]	UVAR	✓	✓	×	✓
[36]	CRUV	✓	×	×	✓
[37]	LAROD	✓	✓	×	×
[39]	GPSR-ABPP	✓	✓	×	✓
[41]	RRPR	×	×	✓	×
[42]	DSGR	✓	×	×	✓
[43]	RGR	✓	✓	×	✓
[44]	LADTR	✓	✓	×	✓

2.5. Cluster-based Routing Protocol (CBRP)

Clustering in UAVNETs refers to dividing the network into interconnected clusters and sub clusters, grouping nodes that are geographically close. Each cluster is coordinated by a Cluster Head (CH), which acts as a temporary Base Station for its cluster. This organization allows hierarchical routing by maintaining paths between clusters rather than individual nodes, enhancing network scalability, route lifespan, throughput, and energy efficiency while reducing routing overhead [45]. Clustering also improves reliability, connectivity, coverage, fault tolerance, and data aggregation. Current clustering protocols are broadly categorized as probabilistic, which use probabilistic models for decision-making, and deterministic, which rely on predefined rules for cluster formation.

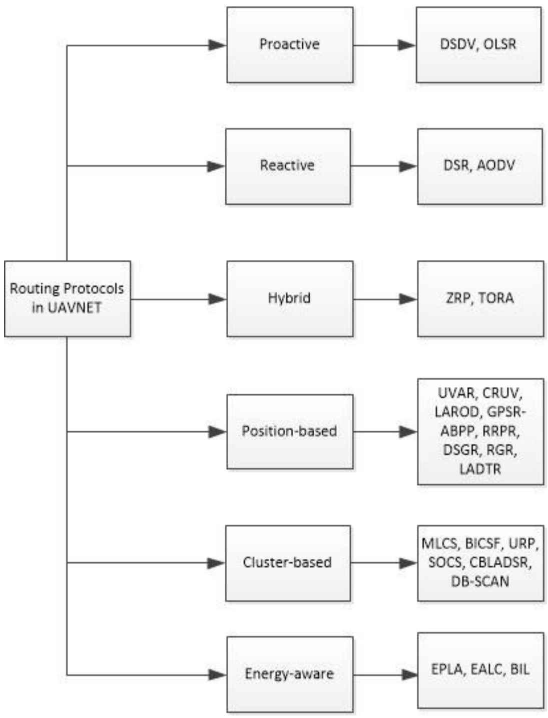

Figure 1. Classification of UAVNET routing protocols.

2.5.1. CBRPs utilizing probabilistic clustering

Probabilistic clustering techniques are primarily intended to discover the optimal routing path, while concurrently enhancing the resilience of the network. Several probabilistic cluster-based routing approaches employ a random selection process to choose the CH. This section offers a thorough examination of the CBRPs that rely on probabilistic concepts.

2.5.1.1. Bio-inspired Clustering Scheme for UAVNETS (BICSF)

A BICSF protocol [46] has been developed to address the current issues associated with topology management and improve communication efficiency in UAVNETs. The process consists of three separate stages: energy-aware cluster formation phase, UAV motion-aware cluster management phase, and cluster maintenance phase. The objectives of this strategy are accomplished by employing a synergistic process that combines Glowworm Swarm Optimization (GSO) and Krill Herd (KH). The BICSF protocol incorporates an energy-aware cluster formation mechanism and utilizes the GSO algorithm for selecting cluster heads. The primary justification for implementing the GSO approach in choosing Cluster Heads (CH) is that it is able to evaluate the status of each UAV by taking into account both its luciferin level plus position. The current state of a glowworm is determined by analyzing its luciferin concentration, its proximity to other glowworms, and the extent of its surrounding habitat. The fitness value is calculated using the equation below.

The rankings of UAVs are solely based on the fitness value associated with the optimal selection of Cluster Heads (CHs). The formula presented in Eq. (1) can be employed for the computation and adjustment of the luciferin value.

$$LF_i(T+1) = (1-\propto)LF_i(T) + \gamma LF(q_i(T))) \tag{1}$$

$LF_i(T)$: Represents the current luciferin value for glowworm i. $LF_i(T+1)$: Indicates the present luciferin value for glowworm i. α: Represents the luciferin decay constant, constrained within the interval [0,1]. γ: Denotes the luciferin enhancement fraction. $LF(q_i(T))$: Considers the objective function of the Glowworm algorithm at its current location (q_i).

In a general context, the CH is identified as the node possessing the highest fitness value. A cluster management system was introduced, inspired by KH. The optimization problem related to the flying node's position was addressed by employing biological genetic approaches, specifically incorporating crossover and mutation operators. The determination of the route detection function in cluster communication is based on the calculation outlined in Eq. (2).

$$RouteDetectionFunction = \frac{REXW_1}{(n_i XW_2)(disXW_3)} \tag{2}$$

W_1: Represents the weight assigned to the measurement of residual energy. W_2: Indicates the weight associated with the count of neighboring UAVs. W_3: Denotes the weight assigned to the distance between UAVs in a given context.

The cluster maintenance phases establish a predetermined energy threshold for each UAV, which is utilized to monitor the current energy level of every cluster member. This threshold is then used to determine whether a cluster member is no longer operational, based on whether their residual energy falls below the defined threshold. This clustering algorithm reduces energy consumption and extends the lifespan of clusters, but its reliance on a passive distance metric for selecting CHs does not consider the necessary safety margin between nodes, which is important for minimizing collisions and improving overall network stability.

2.5.1.2. UAV Routing Protocol (URP)

In [47], the authors introduced a dynamic clustering approach called URP, which utilizes UAVs for monitoring crop health. The URP protocol is a dynamic routing protocol that utilizes a cluster-based approach to gather data within a designated geographical region. The study involves the utilization of a mobile sink node that is based on an UAV to gather data from distributed nodes. The data collection process is carried out through either a random walk or a predetermined path. The UAV transmits a beacon message to initiate the activation of all sensor nodes located in its neighboring areas. Subsequently, it proceeds to form a cluster by taking into account the path and data type. Within the context of URP, the dynamic execution of cluster formation and CH election tasks is observed. Each node participates in the process of electing a CH by utilizing a Bayesian classifier to calculate its probability. The nodes within the routing cluster are categorized into three distinct types: Cluster Members (CMs), Candidate Clusters (CCs), as well as Cluster Head Candidates (CCHs). The process of electing a Cluster Head (CH) involves the participation of both CCHs and UAVs in the nomination of a node to serve as a CH. The CH election process is computed through the utilization of a Bayesian classifier [48]. The protocol can be effectively implemented in rapidly deployed UAVNETs without pre-existing infrastructure, and its use of dynamic clustering significantly enhances network lifetime. However, it was specifically designed for Wireless Sensor Networks (WSNs) supported by a single UAV for crop health monitoring, limiting its broader applicability.

2.5.1.3. Self-Organization Based Clustering Scheme (SOCS)

In [49], the authors introduced the SOCS scheme as a means of enhancing the management of networks and facilitating communication among UAVs. The aim of SOCS is to minimize existing challenges related to topology management in order to enhance communication. The comparative analysis of the SOCS routing protocol is conducted with reference to other bio-inspired protocols. The utilization of the behavioral pattern of Glowworm Swarm Optimization (GSO) a is a fundamental aspect of the SOCS framework for UAVNET. A GSO algorithm is utilized to ascertain the luciferin value and neighborhood range of a glowworm. The selection of GSO for UAVNET was based on its ability to offer an optimal solution within the framework of a glowworm's luciferin value modulation. This facilitates the implementation of the GSO attribute in UAVNETs that are based on clustering. The GSO algorithm incorporates distinct attributes for each glowworm, namely the neighborhood range, which is also referred to as the local decision range and luciferin value. The luciferin value of a glowworm is determined by its objective function and geographical position. The protocol reduces energy consumption within the network and extends the lifespan of clusters; however, it assumes an inter-UAV distance of only five meters, while the distance between UAVs and the central hub may vary, which could affect performance.

2.5.2. CBRPs utilizing deterministic clustering

Deterministic cluster-based routing protocols employ metrics with higher levels of confidence in order to select a CH. The metrics that are frequently encountered in the literature include residual energy, centrality, and proximity and node degree. Nodes acquire information from adjacent nodes through the process of overhearing as well as exchanging messages.

2.5.2.1. Cluster-based location-aided dynamic source routing (CBLADSR)

In [50], the authors introduced a location-aided cluster-based routing protocol known as CBLADSR. This protocol utilizes a node-weight heuristic-based strategy. During the clustering process, a node-weight heuristic algorithm is employed to select the CH and facilitate the formation of clusters. The CBLADSR process is a combination of intra-cluster routing and inter-cluster routing, which respectively pertain to short-range and long-range communications. The primary objectives of CBLADSR are to achieve notable improvements in packet delivery ratio and reduce end-to-end delay. The CH election process utilizes a node-weight heuristic algorithm, in which the weights of nodes are assessed based on certain factors. In the process of selecting a CH, it is necessary to take into account various weight factors, including the appropriateness of node action as a CH, the connectivity degree, the relative speed of the node and the residual energy. During the process of routing, CMs are responsible for facilitating communication within a cluster, while CHs are responsible for managing communication between different clusters. It is presumed that all nodes possess GPS capabilities. The GPS offers the necessary data regarding the location of nodes, enabling the network to make informed decisions regarding node distribution. The use of location-aware routing in UAV networks offers significant benefits, with CBLADSR showing strong performance in both long-range and short-range communication. However, the protocol requires improved precision in location determination to ensure accurate packet forwarding.

2.5.2.2. Density-Based Spatial Clustering of Application with Noise (DB-SCAN)

In [51], the authors introduced the distributive clustering algorithm for UAVNETs. This algorithm incorporates the use of DBSCAN along with Extended Kalman filters (EKFs) to estimate the locations of mobile targets. The aim of the study was to enhance the efficiency of the sensor manager and path planner in order to effectively track multiple agents. The clustering approach was employed to tackle the computational and communication obstacles, thereby enabling the utilization of UAVs for sensing and communication purposes by means of target grouping. The primary objective of DBSCAN routing is to achieve precise Geo-localization of the target. The proposed methodology by the authors involves the utilization of a distributed approach that makes use of a dynamic weight graph and model predictive control, which is based on target density. The objective of this approach was to enhance the effectiveness and precision of mobile agent tracking in UAVNETs. In the context of geo-localization, EKFs are employed for making estimations regarding the position and velocity of a given target. It is suggested that every UAV be outfitted with a GPS and IMU that exhibit inherent noise. The calculation of the k-th target is determined through the utilization of the coordinate transformation system position as given below:

$$q_k^i = q_u^i + L(p_b^i p_g^b p_c^g M_k^c) \tag{3}$$

In this context, the symbols b, g, u, c, and i are used to denote body frame, gimble frame, UAV position, camera frame and inertial frame, respectively, while q_u^i represents the location of the UAV inertial coordinate frame. The symbol L denotes the length of the UAV position to the target, while M_c^k represents the standard vector of target k. Additionally, p_b^i represents the vehicle body frame, p_g^b represents the gimbal frame, and p_c^g represents the camera frame. During the process of cluster formation, the DBSCAN algorithm is capable of creating clusters that exhibit varying sizes and arbitrary shapes, even in the absence of any prior knowledge or primary information regarding the underlying data. The clusters generated are contingent upon the sequence in which the data is assessed and necessitate a minimum threshold of data points referred to as minPts. The concept of a maximum distance ε is employed to determine the inclusion of data points within a given cluster, with respect to a specific point x. The DBSCAN algorithm utilizes the local density of data points in order to identify clusters. In DBSCAN routing, each UAV selects a cluster and obtains the position and velocity of the cluster's centroid, then uses an efficient sensor manager and path planner to locate targets within the cluster. However, the UAVs operate at a consistent altitude of around 100 meters—lower than typical real-world scenarios—and travel at an average speed of approximately 13 meters per second.

This paper thoroughly analysed the benefits and constraints of each approach. Table 6 displays the comparison of parameters utilized to evaluate the efficacy of the aforementioned cluster-based routing protocols. The works in [50] share the property of reducing end-to-end delay. Because the use of location-aware routing has considerable promise in UAV networks. The CBLADSR exhibits exceptional ability in both long-range and short-range scenarios for communication. However, energy consumption is minimal in the protocols discussed in [46, 47, 49, 51].

Table 6. Comparison of parameters used to evaluate proactive routing protocols.

References	Protocols	Packet delivery ratio	Throughput	Overhead	End-to-End delay
[46]	BICSF	✓	✓	×	×
[47]	URP	×	✓	×	×
[49]	SOCS	×	✓	×	×
[50]	CBLADSR	✓	×	×	✓
[51]	DB-SCAN	×	✓	✓	×

2.6. Energy-aware routing protocol

UAVNET rely significantly on energy-aware routing protocols [52] to guarantee the efficient and prolonged operation of UAVs. As UAVs are typically powered by batteries with limited energy capacity, it is crucial to optimize their energy consumption in order to increase their flight duration as well as mission capabilities. Due to UAV mobility, environmental conditions and mission requirements, the UAVNET is a dynamic network in which the connectivity between UAVs and ground stations continuously changes. The energy-aware routing protocols seek to identify the most energy-efficient paths for data transmission, taking into account the network's dynamic nature. In order to determine the optimal routing paths, these protocols typically consider UAVs' remaining energy, link quality and distance.

2.6.1. Energy-balancing Packets Scheduling for Airborne Relaying Networks (EPLA)

The study in [53] focuses on addressing energy imbalance in airborne relaying networks by proposing a packet scheduling algorithm that evenly distributes energy consumption among relay nodes to extend network lifetime and improve efficiency. The approach introduces Energy Replenishment Zones (ERZs), where the relay nodes can restore energy, and schedules packet transmissions based on node energy levels, packet priority, and connectivity requirements. Formulated as an optimization problem, the method aims to minimize energy disparity while ensuring reliable data delivery. Although the results indicate strong potential for applications such as aerial surveillance and disaster recovery, the reliance on simplified network assumptions may limit its effectiveness in real-world, dynamic environments.

2.6.2. Energy Aware Cluster-Based Routing (EALC)

The study in [54] proposes an energy-efficient cluster-based routing protocol, the EALC, designed to address limited flight time and inefficient routing in UAV networks. The protocol applies a K-means density clustering approach, selecting cluster heads based on residual energy and neighbor distance to improve cluster stability and reduce routing overhead. By integrating hierarchical clustering with energy-aware mechanisms, the EALC enhances network lifetime and overall performance. Simulation results demonstrate superior energy efficiency, longer network lifespan, and improved data delivery compared to conventional protocols. However, the study does not thoroughly evaluate scalability, and further investigation is required to assess EALC's effectiveness in large-scale UAVNETs with dynamic topologies.

2.6.3. Bio-Inspired Approaches for Energy-Efficient Localization and Clustering (BIL)

The study in [55] explores bio-inspired techniques to improve energy-efficient localization, clustering, and communication in UAVNETs for wildfire monitoring in remote areas. Inspired by natural behaviors such as swarming, flocking, and decentralized decision-making, the proposed algorithms enhance UAV coordination while reducing energy consumption. Bio-inspired clustering minimizes redundant data collection, while localization methods support navigation in GPS-denied environments. The work also applies ant colony optimization to improve communication efficiency and data routing. Simulation and real-world experiments demonstrate notable gains in energy efficiency, localization accuracy, and communication performance. However, the study highlights scalability challenges, as coordination and communication complexity increase with larger UAV networks.

An analysis has been conducted on the benefits and drawbacks of every protocol. A comparison of the parameters utilised to assess the efficacy of the aforementioned routing protocols is displayed in Table 7. Although energy consumption is s reported to be low in [53-55], the protocol in [53] has the lowest energy consumption, thereby reducing link failures.

Table 7. Comparison of parameters used to evaluate energy-aware routing protocols.

References	Protocols	Energy consumption	Network lifetime	Cluster lifetime
[53]	EPLA	✓	✓	×
[54]	EALC	✓	✓	✓
[55]	BIL	✓	✓	✓

3. COMPARISON OF ROUTING PROTOCOL

This section provides a qualitative analysis of the existing routing protocols, with a particular focus on their prominent attributes and characteristics. Routing protocols utilize diverse routing metrics to establish the optimal path from the source (S) to the destination (D). The choice of a suitable routing protocol is contingent upon the particular application needs, network fluctuations, and resource limitations. Additionally, the assessment of reliability and performance of the selected routing path heavily relies on the routing metrics employed [56].

Table 8. Contrasting evaluation of UAVNET routing protocols.

References	Routing protocols	Type of routing	Overhead	Mobility	Latency	Complexity
[21]	Proactive	Adaptive	Yes	Slow	Low	Moderate
[27]	Reactive	Adaptive	Yes	Fast	High	Moderate
[31]	Hybrid	Adaptive	Yes	Average	High	Moderate
[34]	Position-based	Adaptive	Yes	Average	High	High
[45]	Cluster-based	Adaptive	Yes	Average	High	High
[52]	Energy-aware	Adaptive	Yes	Average	Low	Moderate

Table 8 offers a comprehensive summary of the comparative analysis performed on the primary routing protocols utilized in UAVNETs. In recapitulating the discussion presented in the preceding section, proactive protocols utilize routing tables for route storage, while reactive protocols employ source-based routing. Hybrid protocols combine aspects of both proactive and reactive protocols. Position-based protocols use GPS technology for geographical location determination, and cluster-based protocols are structured around clustering. Energy-aware routing is implemented to minimize energy consumption during routing. Additionally, complexity is a notable consideration, with proactive, energy-aware, hybrid and reactive protocols demonstrating lower complexity levels compared to position-based and cluster-based protocols.

The classification of UAV routing protocols according to their delivery methods is illustrated in Table 9. Simulations tools are employed to conduct performance assessments and validations of these protocols. Different simulators use varied techniques that result in variations across protocols. The mobility generator and subsequent movement of UAV nodes also differ among simulators. Moreover, distinct routing metrics are employed by various simulators, with packet delivery ratios, end-to-end delay, route setup time, energy consumption, and network lifetime commonly considered essential performance indicators.

Table 9. Comparison of proactive, reactive, hybrid, position-based, cluster-based, and energy-aware routing protocols

References	routing protocol	Evaluation metric	Latency	Simulation tool	Type of network
			Proactive routing		
[22, 23]	OLSR	O	Medium	OPNET, QualNet	MANET/ UAVNET
[24, 25]	DSDV	O	High	NS-2, GloMoSim	MANET/ UAVNET
			Reactive routing		
[28]	DSR	ED	-	NS-2, OPNET, OMNET++	MANET/ UAVNET
[30]	AODV	PD, ED	Medium	NS-2, OPNET, OMNET++	MANET/ UAVNET
			Hybrid routing		
[32]	ZRP	ED	Low	QualNet, GloMoSim	MANET/ UAVNET
[33]	TORA	-	Low	NS-2, OPNET	MANET/ UAVNET
			Position-based routing		
[35]	UVAR	PD, ED	High	NS-2	UAVNET-VANET
[36]	CRUV	PD, ED	High	NS-2	UAVNET-VANET
[37]	LAROD	PD, O	-	NS-2	UAVNET
[39]	GPSR-ABPP	PD, ED, O	Medium	NS-3	UAVNET-VANET
[41]	RRPR	AH, RS	-	MonteCarlo	UAVNET
[42]	DSGR	PD, ED	Low	NS-3	UAVNET
[43]	RGR	PD, ED, O	Low	NS-3	UAVNET
[44]	LADTR	PD, ED, O	Low	NS-3	UAVNET
			Cluster-based routing		
[46]	BICSF	PD, EC, CL	Medium	MATLAB	UAVNET
[47]	URP	DN, EC	Medium	MATLAB	UAVNET
[49]	SOCS	EC	Low	MATLAB	UAVNET
[50]	CBLADSR	ED, PD	Low	MATLAB	UAVNET
[51]	DB-SCAN	EC	Low	MATLAB	UAVNET
			Energy-aware routing		
[53]	EPLA	EC, NL	Medium	MATLAB	UAVNET
[54]	EALC	EC, CL	Low	MATLAB	UAVNET
[55]	BIL	EC, CL	Medium	MATLAB	UAVNET

O: Overhead, ED: End-to-end delay, PD: Packet delivery ratio, AH: Average No. of Hops, RS: Route setup time, CL: Cluster lifetime, EC: Energy consumption, DN: Number of dead nodes, NL: Network.

4. CHALLENGES IN UAVNET

UAVNET is very popular in several applications, but it is facing various challenges [57], which are listed below.

4.1. Technological limitations

When it comes to drone technology, payload capacity and flight time are always trade-offs. UAVs typically use lightweight lithium-ion batteries on board for power. But they are not comparable to other batteries in terms of power backup. The increase in payload leads to an increase in endurance. As a result, the mission may not be completed. Therefore, further research is necessary.

4.2. Security, privacy and safety concerns

The rapid use of drones has raised a number of life-threatening issues, raising safety and security concerns. A drone's airworthiness, malicious activity and interference with public property are serious safety concerns, making drone use a serious issue. These concerns cannot be addressed using current approaches, which do not match reality and do not guarantee the safe use of drones. In order to prevent interference with airspace, air traffic controls must be established and monitored. Jamming attacks can interfere with UAVs.

4.3. Communication

Communication in autonomous UAV clusters is a major challenge due to frequent topology changes affecting the high-speed routing mechanisms of mobile nodes. As a result, the quality of service declines. Power is a critical issue for UAV nodes. These issues affect network performance.

4.4. Connectivity

There are two primary types of connections in UAVNET: links between UAVs and links between UAVs and the Ground Control Station (GCS). Due to the high mobility in UAVNET, link failures occur frequently and link failures reduce the lifetime of the network. Communication links between UAVs are extremely vulnerable.

5. CONCLUSIONS

This paper presents an extensive overview of various routing protocols designed for UAVNETs. Routing protocols are classified into several types, such as proactive, reactive, hybrid, position-based, cluster-based, and energy-aware routing. The study analyzes these protocols, emphasizing diverse routing techniques, evaluation metrics, and the pros and cons associated with each. The following are some findings that have emerged as a result of this study:

- Proactive and energy-aware routing protocols exhibit reduced latency due to their moderate to low complexity and mobility.

- Routing protocols that are position-based, reactive, hybrid, or cluster-based have high latency due to their moderate to high complexity as well as mobility.

The objective of this analysis is to compare existing routing protocols based on key parameters and metrics. In conclusion, this study addresses current issues and identifies potential future challenges. To the best of our knowledge, this paper marks the initial publication providing a comprehensive analysis across all categories of routing protocols. Our findings underscore the importance of considering scenarios with low node density and high mobility when evaluating routing protocols for UAVNETs.

CRediT authorship contribution statement. Surabhi Patel: Conceptualization; Data curation; Methodology; Formal analysis; Investigation; Writing – original draft; Visualization. Heman Pathak: Data curation; Visualization; Writing – review & editing; Validation; Supervision.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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