Routing Protocols for Unmanned Aerial Vehicle-Aided Vehicular Ad Hoc Networks: A Survey

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ABSTRACT In intelligent transportation systems, a vehicular ad hoc network (VANET) has a significant impact in enhancing road safety, traffic management efficiency, and in-vehicle infotainment features. Routing in a VANET is hampered by frequent link disconnection for non-line-of-sight communication due to roadside obstacles, high mobility, and frequent topological changes. With the help of three-dimensional movement capability, an unmanned aerial vehicle (UAV) can drastically improve the routing experience of a VANET, by increasing the line-of-sight probability, better connectivity, and efficient store-carry-forward mechanism. As a result, various routing protocols with different objectives have been reported for UAV-aided VANETs. Several surveys have been conducted based on different routing protocols for VANETs so far. However, to the best of the authors' knowledge, no survey exists till now that dedicatedly covers routing protocols for UAV-aided VANETs. This survey paper presents a comprehensive review on state-of-the-art routing protocols for UAV-aided VANETs. The protocols are categorized into seven groups in terms of their working mechanism and design principles. The shortcomings of the protocols are identified individually by critically analyzing them with regard to their advantages, disadvantages, application areas, and future improvements. The routing protocols are qualitatively compared with each other in tabular format as well on the basis of various design aspects and system parameters. In particular, not only performance and special features but also optimization criteria and techniques are extensively discussed in addition to the tabular comparison. Furthermore, open research issues and challenges are summarized and discussed.

INDEX TERMS Unmanned aerial vehicle, vehicular ad hoc network, mobile ad hoc network, routing protocol, drone, roadside unit, multihop routing.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) are a type of mobile ad hoc networks (MANETs) in which mobile vehicles can communicate with each other via wireless links [1]. Currently, vehicles are equipped with on-board units (OBUs) including various sensors and transceivers [2]–[5]. Using OBUs, vehicles interact with other communication objects such as roadside units (RSUs), unmanned aerial vehicles (UAVs), and ground stations (GNs). A VANET plays the most important role in an intelligent transport system (ITS) [3]. In an ITS, VANET is used for public safety [6], traffic

prediction [7], driving safety [2], driver behavior detection [4], and entertainment purposes.

UAVs are lightweight aircraft that can be operated remotely or in a pre-programmed way. Generally, these devices are equipped with various sensors, computational units, cameras, a global positioning system (GPS), transceivers, etc. UAVs are used in many military and civilian applications [8]. Ad hoc relaying [9], emergency communications [10], traffic monitoring, remote place observation, relief operation, geographical monitoring, surveillance, crop monitoring [11], parcel delivery [12], homeland protection, farming, post-disaster operation [13], [14], public safety [15], autonomous tracking [16], data ferrying, border observation [17] are some usage examples of the uses of UAVs. As an effective networking tool, the UAV has some distinctive

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features including low cost, store-carry-forward (SCF) capability [18], and, a good line of sight (LOS) [19]. A UAV-aided network is also rapidly deployable, compared to any other static infrastructure-based networking system [12]. Hence, using UAVs as a mobile infrastructure network backbone for a remote location within a short duration is a preferable option [20]. Extensive research is being conducted on UAV-aided networks.

A UAV-aided VANET is a heterogeneous network architecture, where the vehicular network is supported by the UAV. In such networks, the vehicles can establish vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and infrastructure to infrastructure (I2I) communication with the assistance of UAVs for message relaying and carry-forwarding. In the traffic monitoring system, a UAV-aided VANET adds extra functionalities and opportunities. This networking scheme can also contribute to roadside safety and incident reporting [21]. Pre-alerting of the road conditions or setting up a temporal traffic indicator is possible with the help of this kind of networking. Specialized UAV mobility modeling with direction optimization can ensure a maximum connection time with the vehicles. UAVs give the flexibility to find a suitable position in three-dimensional space. As a result, UAVs were also experimented in the role of temporary RSU [22], where the infrastructure was limited or compromised. In such environment where the LOS communication is hampered due to obstacles, some experiments were done for finding out the optimal place to establish LOS UAV-ground vehicle communication [23]. Delay performance in such obstructed place is an important fact and researchers have also focused to optimize the delay performance for communication between UAV and ground vehicles [24]. In a disaster-affected area, UAV-aided VANETs can play an important role in establishing temporal connectivity solution to other MANET devices with the aid of connected rescue vehicles. It is possible for UAVs to create and maintain continuous connection with the vehicles because of the variable altitude, speed, and obstacle avoidance characteristics. These criteria assist in the tracking of any vehicle and, by utilizing this mechanism, the law enforcement team benefits [12]. The overall quality of experience (QoE) can be improved by integrating UAVs with ITS [25]. Research on vehicle automation is an active area of study in the current industrial climate. Several companies have already started to build automated cars. These cars are heavily dependent on network connectivity [26]. In a remote location or a disaster-affected area where the infrastructure is compromised, these cars will not be useful without emergency connectivity support. To ensure the productivity of automated cars, a rapid deployable continuous connectivity support should be available in these areas. UAV-aided VANETs can play such a role in this case.

To achieve the full benefits from UAV-aided VANETs architecture, several important issues related to routing protocol must be addressed [12]. Given that VANETs are highly mobile with unpredictable movement, vehicular density differs depending on the location and time. Based on the relative speed, a UAV also requires sufficient time for a vehicle to transmit its data. Owing to the dynamic environment and frequent topology changes, maintaining connectivity during the transmission time is difficult. In addition, the design of a routing protocol for UAV-aided VANETs is also a challenging task. Because of the usefulness of UAV-aided VANETs, a number of routing protocols for UAV-aided VANETs have been reported in the literature.

UAV-aided VANETs are relatively newer but have the possibility of solving well-known VANET problems such as control packet overhead, frequent link failure, non-line of sight (NLOS) communication, and connectivity disconnection in the sparse region. This article summarizes the existing routing solutions in UAV-aided VANETs, which will work as a starting point for new researchers and engineers in this field. The rigorous comparison and discussion will help them to get a good insight into existing works in this field.

A. CONTRIBUTIONS OF THE STUDY

In this article, we extensively investigate the routing protocols designed for UAV-aided VANETs to address key features and characteristics. We then qualitatively compare the protocols with each other. The major contributions of this article are as follows:

- As preliminaries, in Section II, the routing protocols for VANETs and UAV networks are also previewed separately because the heterogeneous architecture of UAV-aided VANETs consists of both VANETs and UAV networks.
- The routing protocols for UAV-aided VANETs are classified into seven categories according to their characteristics and routing paradigms. The taxonomy of the routing protocols for UAV-aided VANETs is also given Section III.
- Each routing protocol is discussed with respect to its operational principles, outstanding features, benefits, and drawbacks. In particular, the protocols are critically reviewed by examining their advantages, disadvantages, application areas, and possible future improvements in Section III.
- The routing protocols are qualitatively compared with each other in terms of their important characteristics, various design aspects, optimization parameters, key designing factors, and performance evaluation techniques. The comparisons are arranged in four different tables in Section IV. Our opinion is also added to give the readers a good insight about the discussed protocol's optimization technique and evaluation criteria.
- Finally, open research issues and challenges are summarized and technically discussed by considering possible future improvements of the routing protocols for UAV-aided VANETs in Section IV.

B. ORGANIZATION OF THE PAPER

The remainder of this paper is organized in several sections. Figure 1 shows the graphical representation of the

paper organization. In Section II, recently reported routing protocols for VANETs and UAV networks are briefly described, as preliminaries. In Section III, the protocols for UAV-aided VANETs are classified into six categories and extensively reviewed with respect to their operational principles, outstanding features, advantages, disadvantages, application areas, and future improvements. In section IV, the protocols are qualitatively compared with each other in terms of their important characteristics, performance evaluation criteria, various design aspects, and objective parameters. The comparison are given in tabular format and described extensively in the two subsections. In Section V, important research issues and challenges are summarized and discussed. Finally, the paper is summarized as conclusion in Section VI.

In this paper, a number of equations are given. Table 1 contains the notations and their meaning used in this paper.

II. PRELIMINARIES

The routing protocols for VANETs and UAV networks are briefly summarized in this section. They are presented with respect to their key points only.

A. ROUTING PROTOCOLS FOR VANETS

There are numerous studies on routing protocols for VANETs. In [27], the authors applied the concept of the moving zone clustering technique to a VANET scenario. These proposed models are based on moving zones of vehicles that are moving in the same direction. In a moving zone, one vehicle is elected as the "captain" node. The captain stores and manages information about other vehicles. Vehicles only share their information when a drastic change occurs in their movement and direction. In [28] the authors proposed a VANET routing protocol based on the quality of framework (QoF). In the proposed model roads are modeled according to urban road characteristics. Transmission cost and packet delivery ratio are taken into consideration to measure the QoF. This routing protocol follows different communication methods for different positions of the destination nodes. An intersection-based connectivity aware routing protocol is proposed in [29]. This research introduces a new formula for the connectivity analysis of road sections. Location error-resilient geographical routing (LER-GR) protocol uses a Raleigh distribution-based fault estimation technique to inaccuracies in GPS calculations [30].

Ant colony optimization is applied in the enhanced geographical source routing (EGSR) protocol [31]. In this protocol, the ant-named small control packet is used to calculate the weight of road segments. A bio-inspired opportunistic-unicast routing protocol based on attractor selector (URAS) uses a multi-attribute decision-making strategy to find the minimum number of hops required to reach the destination [32]. It is an adaptive routing protocol and attempts to find the optimal path even after the establishment of a primary route. In [33] the authors discussed the impact of traffic lights on vehicular connectivity and presented a traffic light-aware routing protocol (TLRP).

TABLE 1. List of notations.

ι	Single link
r_ι	Maximum capacity of a link
d_ι	Transmission delay of a link
δ	Given constraint
$Score_i$	Connectivity score of a road segment
$TOTAL_{Vehicles}$	Number of total vehicles
L_j	Number of vehicles in the left side of a vehicle
R_j	Number of vehicles in the right side of a vehicle
P_{rG2A}	Received power in the ground from aerial vehicle
L	Path loss due to the distance
P_{tG2A}	Transmission power of the aerial vehicle
$\xi_{LoS,}$	Shadow fading of LOS communication
ξ_{NLoS}	Shadow fading of NLOS communication
$N(Z)$	Total number of nodes in a single path
σ	Real distribution of the vehicles
$PointX_i$	X- co-ordinate of a node
$Score_g$	Connectivity score of the ground vehicle
R_v	Transmission range of a vehicle
D_w	Shortest road segment
P_{close}	Probability of the already visited location
M	Area
N	Routes
c	Category
K	Preferred regions
V_{MAX}	Maximum speed of a UAV
α_{ui}	Azimuth angular speed of a UAV
T_{max}	Delay constraint
ϵ	Violation probability
a	Number of drones
G_{total}	Amount of total generated overhead
$O_{u_{ij}}$	Overhead between vehicle i and j
E	Energy consumption rate
α, β	Weighting parameters of the transmission time and energy consumption
$s^{(k)}$	System state at kth time
ρ_1	Link quality between the UAV and the OBU
ρ_2	Link quality between a RSU and an OBU
$a_{1,i}$	Strategy of a player
ρ_3	Signal to interference plus noise ratio (SINR) between RSU and the UAV
P_e	Bit error rate (BER)
P_ID	Vehicle's unique id
P_{sd}	Path availability from source to destination
W	Mean intra-cluster distance
$E[T']$	Average carry delay
$E[V']$	Space mean speed
$E[d']$	Carry distance
μ	Pay-off function
$h_{1,i}$	Strategy of a player

Direction-aware best forwarder selection (DABFS) [34] is a recently published routing protocol designed for VANET architecture. This routing protocol considers the vehicle's direction for both way which makes the model more appropriate for practical application. DABFS utilizes the Hamming distance to calculate the movement direction of the neighboring nodes so that the protocol can propagate the data through the best route. The protocol is also adaptive to frequent topological changes. Keeping the direction in mind, a medium access control protocol named priority-based direction-aware media access control (PDMAC) was introduced for VANETs [35]. Besides the direction component, PDMAC also consid-
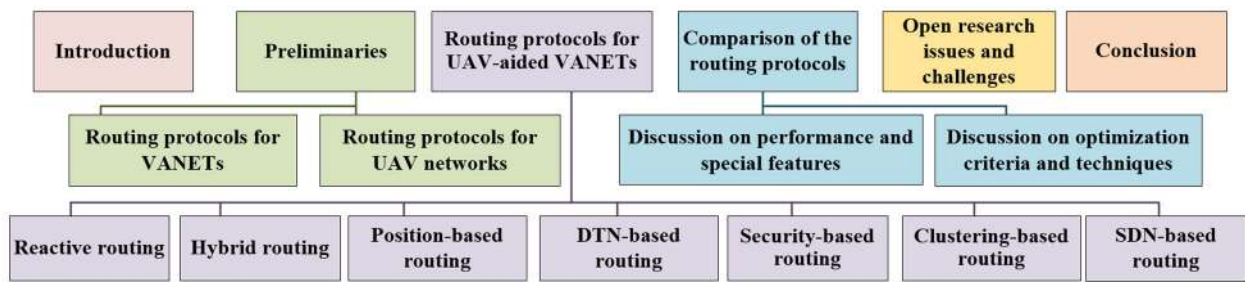
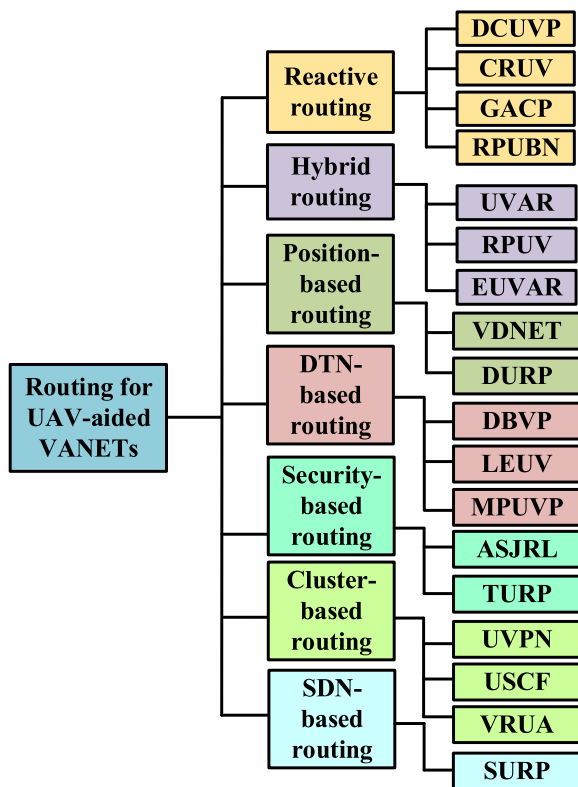**FIGURE 1.** Graphical representation of paper organization.

FIGURE 2. Taxonomy of the routing protocols for UAV-aided VANETs.

ers the type and priority of messages as design parameters. GreeAODV [36] is an energy-efficient routing protocol for VANETs. This protocol chooses intermediate hops by considering energy as the first parameter. This protocol is best suitable for battery-powered vehicles in urban areas.

In [37], location-based routing protocols for VANETs are surveyed extensively by pointing out the existing issues, challenges, and solutions. Particle swarm optimization (PSO) based clustering and routing techniques is proposed in [38]. An intelligent firefly-based algorithm with levy distribution is used in [39] to develop a multicast routing algorithm for VANETs. GeoOpps-N is a topology-based routing protocol designed specially to establish communication between the buses and public transportation systems (PTS). This routing

protocol chooses nodes that can pass data to the RSU within the shortest interval. Apart from the mentioned protocol, there are several surveys based on the routing protocol of VANETS such as [2], [40], etc.

B. ROUTING PROTOCOLS FOR UAV NETWORKS

Compared to VANETs, ad hoc networking for UAVs is a relatively new idea. In [13], the authors proposed a routing protocol called location-aided delay-tolerant routing (LADTR) for post-disaster management operations. This protocol has a prediction mechanism to detect the position of the destination node. The selection of the forwarding node also depends on the prediction mechanism. In the case of disconnectivity, the protocol uses a store-carry-forward (SCF) recovery policy. The adaptive hello interval (EE-hello) was introduced in [41]. By scheduling a hello-interval, this routing protocol conserves the energy of the UAV. The protocol also adopts a technique to optimize the UAV number. Position-aware secure and efficient routing approach (PASER) is a mesh topology-based secure routing protocol for which the author showed that improved security against attacks is possible compared to the well-known security mechanism, IEEE 802.11sГi [42].

A specialized three-dimensional routing protocol for UAVs was presented in [43] that ensures an optimal height for the maximum airtime. This three dimensional (3D)-graph-based algorithm also includes a mechanism for avoiding accidents and supports manned aircraft operation. An integer linear problem (ILP) was formulated to assume control of the routing decision in [44]. The formula derives a scoring system based on the visited locations.

GeoUAVs [45] is a geocast-based UAV routing protocol that takes the 3D movement of the node, practical topological change, and the reliability of the nodes into consideration for disseminating data to destination nodes towards specific geolocation. An elaborated review analysis is given in [46] by discussing the UAV routing protocol designed for the agricultural sector. Keeping energy consumption and delay, a Q-learning based multi-objective UAV routing algorithm is introduced in [47]. Besides energy consumption and flight status, link stability is also taken into consideration for designing the routing protocol in [48]. UAV is a favorable medium for post-disaster management operations. In [49],

a routing protocol for such a scenario is proposed. Apart from the aforementioned research, there are several survey studies done on UAV routing protocols [50]–[54]. The comparisons, short discussion, and taxonomies provided in the surveys are helpful for future research into UAV-based routing.

III. ROUTING PROTOCOLS FOR UAV-AIDED VANETS

In this section, the routing protocols are divided into six different categories as shown in Fig. 2. They are classified according to their dominating characteristics. Most of the routing protocols use GPS or clustering technique; however, a few protocols use them in routing decisions. On the other hand, SCF technique is utilized by most of the protocol to achieve delay tolerant characteristics. These protocols are extensively discussed with respect to their operational principles and outstanding features. In particular, they are critically examined by emphasizing their advantages, disadvantages, application areas, and future improvements.

A. REACTIVE ROUTING

Reactive routing establishes the route when any node needs to transmit data. This type of routing protocol saves bandwidth as it does not broadcast any periodic control packet to maintain the route. However, it also increases the end-to-end delay.

1) DELAY CONSTRAINED UAV-AIDED VANET ROUTING PROTOCOL (DCUVP)

Fan *et al.* [55] proposed a delay-constrained routing protocol for UAV-aided VANET called DCUVP. The routing scheme attempts to maximize the throughput, whereas the delay is maintained below a threshold value. The network is depicted as a weighted graph G (V, E) problem, where V is the set of vertices and E is the set of edges. The edge from graph theory indicates the available communication link and V represents both the ground vehicles and UAVs. Throughput maximization is derived by the sum of the transmission rate of the selected links on the data delivery path. The protocol attempts to select the path with the maximum transmission rate while maintaining the transmission delay below the limit. The value of an edge (e) is expressed by (we, de) where we represent the transmission rate and de represents the transmission delay. The maximization problem can be formulated as follows:

$$max \sum_{\iota \in L} f(r_\iota) \cdot x_\iota s.t., \tag{1}$$

where ι denotes a link, the maximum capacity of the link is denoted by r_ι, d_ι represents the transmission delay of the link, and δ denotes a given constraint. The value of x_ι depends on the selected link. If the selected link is ι, then the value of x_ι is 1, otherwise, it is 0. The throughput maximization is formulated as the 0/1 knapsack problem. Given that the network is assumed to be a multi-edged weighted graph, there might exist more than one (Wi, Di) value for a node i. The parameter (Wi, Di) is the pair of summation of the transmission rate and transmission delay from the source to the

node i. A function called trim is used to remove unnecessary values from the list of (Wi, Di). The source node first sends a request for channel information from its neighbors. Based on this information node, (wi, di) is calculated and the trim procedure is implemented to remove unnecessary values from the list.

a: ADVANTAGES
The protocol ensures a limit of the data delivery delay that can facilitate time-bounded operations for UAV-aided VANET scenarios.

b: DISADVANTAGES
The transmission rate and transmission delay are subject to be changed within a short span. The calculation performed for a path will expire and a recalculation is required by the DCUVP for an accurate assumption. This link checking causes an extra overhead of the network and the calculation process for throughput maximization requires extra time.

c: APPLICATION AREAS
Best suited for urban areas with an appropriate density of vehicles. Future improvements: DCUVP will work more efficiently if the protocol considers the link-state and predicts the lifetime of the link, along with the transmission rate. Data delivery can also be ensured in a sparse network if the protocol introduces variable thresholds for data delivery delay.

2) CONNECTIVITY-BASED TRAFFIC DENSITY AWARE ROUTING FOR UAV-AIDED VANET (CRUV)

Oubbati *et al.* [56] presented a traffic density-based routing protocol for UAV-aided VANET called CRUV. The connectivity and lifetime of the path were considered to be major concerns in data routing decisions. The connectivity of any road segment was measured with the assistance of exchanged hello packets between vehicle to vehicle and vehicle to UAV. The use of UAVs assists the vehicle in the transmission of its data packet when direct communication cannot be established with the destination vehicle. The protocol uses a greedy forwarding technique to establish a connected path and a carry-and-forward technique in the case of a disconnected path. Traffic density and connectivity are calculated in a distributed manner among vehicles. The structure of the hello packets is modified so that the vehicles and the UAV can calculate and broadcast connectivity and density measurement. Fig. 3 shows an example of the hello packet's structure. The packet includes the node type (NT), number of one-hop neighbors in the left (DLN) and right (DRN), total number of neighbors in the left (VL) and right (VR), selected intersection (SC), selected forwarding solution (SFS) and the intersection connectivity in the left (Lj) and right (Rj).

The vehicles get information about other vehicles from their furthest reach limit by broadcasting hello packets. The total number of vehicles in a segment is calculated based on the VL or VR field of the hello packet. This value is then

NT	SFS	SC	DLN	DRN	VL	VR	Lj	Rj
Vehicle	/	/	2	2	5	5	1	1

FIGURE 3. Structure of the hello packets used by CRUV routing protocol.

used to calculate the score of the segment using the following equation:

$$Score_i = \frac{TOTAL_{Vehicles}}{D_w} \cdot (L_j \times R_j),\qquad(2)$$

where DW is used to express the Dijkstra weight, $Score_i$ is the connectivity score of the segment, and $TOTAL_{Vehicles}$ is the number of total vehicles on the road segment. To participate in a routing decision, the vehicles in the intersection compare their calculated scores to the UAV's calculated scores. If the latter is higher, then the packet is transferred to the UAV that acts as an SCF node for delivery to the highest connected intersection vehicle.

a: ADVANTAGES

A comparison between the global connectedness score from the UAV and the local connectedness score from the vehicle facilitates more efficient and effective routing decisions.

b: DISADVANTAGES

While acting as an SCF node, the UAV may require a long interval when the degree of connectivity of the destination segment changes. In the simulation, the speed of the vehicle was assumed to be approximately half the speed of the UAV, which is sufficient time while the degree of connectivity might changes.

c: APPLICATION AREAS

This protocol is suitable for roads with small segments. The roads should be dense for the ideal operation of this protocol. This protocol benefits from traffic signals.

d: FUTURE IMPROVEMENTS

Future prediction for the connectedness of the road segments will improve the suitability of the protocol for the SCF mode.

3) GROUND-AIR CO-OPERATIVE ROUTING PROTOCOL (GACP)

Jia *et al.* [57] proposed the GACP for the UAV-assisted VANET protocol. This protocol aims to determine the optimal number of UAVs and the altitude for a given connectivity threshold of vehicles. To prevent interference among these links, the system considers three different channel modeling for air to air (A2A), air to ground (A2G) and ground to ground (G2G) networks. Connectivity is determined with the help of different path loss models for different types of networks. The received signal power is calculated using the following equation:

$$P_{rG2A}\,(dB) = \begin{cases} P_{tG2A} - L - \xi_{LoS}, LoS\ links \\ P_{tG2A} - L - \xi_{NLoS}, NLoS\ links \end{cases}\qquad(3)$$

where P_{rG2A} denotes the received power for the ground to air (G2A) sub-network, and L is the path loss due to the distance between the A2G and G2A links. The parameter P_{tG2A} is the transmission power of the aerial vehicle, and ξ_{LoS}, ξ_{NLoS} are the shadow fading of the LOS and NLOS channels. Different environmental factors and elevation angles are considered to calculate the path model. G2G channel modeling is used to determine the path loss model using the Manhattan grid layout path loss model. The threshold of connectivity is determined by the value of the signal-to-noise ration. It is derived in two different ways for A2A and G2G links. In GACP, a vehicle can communicate with other vehicles with or without the assistance of UAVs in a multi-hop manner. The routing protocol sets the UAV's altitude to achieve the highest average connectivity to establish direct communication with other UAVs. If a vehicle is connected to multiple UAVs, it chooses the path with the minimal hop.

a: ADVANTAGES

GACP calculates the path loss model in a very efficient way by considering different environmental factors and elevation angles. G2G communication is analyzed from three different perspectives that also allows the protocol to perform better routing decisions.

b: DISADVANTAGES

The A2A communication is assumed to have consistent LOS but altitude optimization for the A2G or G2A network can disrupt the LOS of the A2A networks.

c: APPLICATION AREAS

This protocol is optimized for roads with a grid-based layout.

d: FUTURE IMPROVEMENTS

The number of UAVs can be revised to create a multi-hop fully connected network for the A2A network, after the establishment of a fully connected G2A network.

4) ROUTING PROTOCOL FOR UAV-AIDED-VANET BACKBONE NETWORK (RPUBN)

Oubbati *et al.* [58] proposed RPUBN routing protocol for UAV-based backbone networks to assist emergency ground vehicles in the urban areas. In RPUBN, the deployed UAVs collect the information about the road condition by exchanging beacon messages with the ground vehicles and try to find out any road accidents and hazards by calculating the mobility of the vehicles on the road. The network of the UAVs is organized in a durable way by following the constraints of connected dominated set (CDS) characteristics for constructing the backbone network. A UAV in the network can be a free UAV or a part of the backbone network. The roads are assumed to be divided into multiple zones. The exchanged hello packets between a UAV and a ground vehicle contains the position and speed of the ground vehicles. The backbone network members are selected based on their residual energy and mobility. The proposed protocol exploits one marking

system for making the UAV backbone network. At the initial stage, except for the target service (TS) node, all the UAVs are assumed to be unmarked. While routing data after forming the CDS network, the UAV nodes take the residual energy level and the robustness of the link to make the routing decision. After detecting any road accident, the host UAV generates RREQ messages to find out the route to the TS. While the packets traverse through the CDS network, they gather information about the residual energy and link lifetime. After ten seconds of a lifetime, every RREQ packet automatically gets dropped. The TS runs the Dijkstra algorithm to find out the shortest path after receiving the RREQ packets considering the score calculated on the basis of the segments score and residual energy of the UAV nodes in the CDS network.

a: ADVANTAGES
Network formation based on CDS property has a positive impact on the end-to-end delay and packet delivery ratio. Residual energy consideration helps RPUBN to predict the network failure reducing packet drops.

b: DISADVANTAGES
RPUBN is not a delay-tolerant routing protocol. This protocol does not provide any solution in case of a networking hole as it assumes that the network will always have an alternate path to delivery.

c: APPLICATION AREA
RPUBN is suitable for urban areas. Mission-critical places where emergency relief should be given within the shortest possible time are the perfect places to deploy such service.

d: FUTURE IMPROVEMENTS
Store-carry-forward mechanism will give RPUBN a delay-tolerant capability.

B. HYBRID ROUTING
Hybrid routing protocols attempt to minimize the disadvantages of reactive and proactive routing protocols. They attempt to minimize the delay and latency of the reactive protocol and to optimize the network bandwidth of the proactive protocol. Zone-based routing was introduced as an example of this type of protocol.

1) ZONE-BASED ROUTING PROTOCOL FOR UAV-AIDED VANET (ZRPUV)
Oubbati et al. [59] proposed ZRPUV for the UAV-aided VANET architecture. The routing protocol uses fixed-size control packets to reduce network overhead. ZRPUV also applies a prediction technique for the link expiration time estimation. Moreover, the protocol divides each road segment into zones based on the communication range of the vehicles. In the route discovery phase, the source node broadcasts route request (RREQ) packets. Fig. 4 shows the route packets of the RREQ, route reply (RREP), and the format of the data packet header used by the ZRPUV protocol.
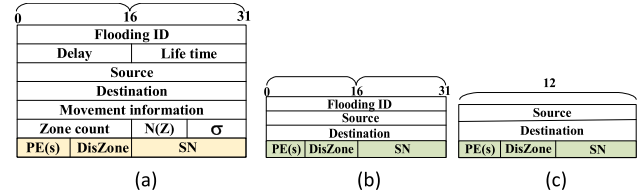
FIGURE 4. Structure of the control packets used by ZRPUV: (a) RREQ packet format, (b) RREP packet format, and (c) Data header's packet format.

The numbers on the top of each packet indicate the packet's size in bytes. The source and destination fields represent the address of the source vehicle and the destination vehicle. The RREQ packet is dropped when the value of the lifetime field of the packet is expired. The zone count shows the total number of visited hops. Broadcast storms are mitigated using the sequence number (SN) and the flooding id field. If any node receives an RREQ packet with an SN and flooding id that matches any previous RREQ packet, then the new RREQ packet is immediately dropped. Given that the protocol uses fixed-size control packets, the full path information is not stored. The movement information field of the packet is edited by each hop and these hops include their personal information such as speed, position, and direction. A few fields are gradually edited in the discovery process to construct the path. Path expiration (PE) is the minimum lifetime of a link. This field is edited only if the newly calculated PE is larger than the stored value. All types of packets have PE, DisZone, and SN fields. These packets are used by the hops to determine whether the link is still viable or not. The PE is calculated in two different ways for vehicles with the same altitude and with different altitudes. When the RREQ packet arrives at the destination, a score is calculated for all the discovered paths using the following equation:

$$Score = \left\lfloor \frac{PE}{Delay} \right\rfloor \times \left(\frac{N\,(Z)}{1+\sigma} \right), \qquad (4)$$

where *Score* is the connectivity score of the road segment, $N\,(Z)$ denotes the total number of nodes in a single path, *Delay* represents the time required for data delivery, and σ indicates the real distribution of the vehicles. After calculating the score, the destination node updates the RREP packet and transmits it back to the source node. The path with the highest score receives a higher priority than the others. Based on the address of the destination, SN and the flooding ID fields in the RREP packet the forwarders in every zone and select the next zone to forward the data packet. In the case of a path failure, the routing model adopts a recovery system when a disconnection occurs, and the carrying node chooses the closest node to the destination to forward the packet. The proximity of the zones is determined by the geographical position of the node. In addition, one route error (RERR) packet is generated by the carrier node to re-initiate the discovery process. Furthermore, any disconnected zone can be addressed by the UAV and future path failure can be prevented.

a: ADVANTAGES

The division of roads into zones makes it easy to identify the disconnected segments. Such division also assists in the implementation of the necessary solution for a sparsely connected graph. The path expiration calculation has a significant impact on the appropriate path selection in the destination node. The overhead optimization and broadcast mitigation technique also conserve bandwidth.

b: DISADVANTAGES

The energy of the UAVs should be taken into consideration. UAV's specific mobility model is not provided.

c: APPLICATION AREAS

Suitable for the urban environment for any vehicular density.

d: FUTURE IMPROVEMENTS

NLOS might also arise in city areas for UAVs because of the skyscraper and FAA rules. It is a common phenomenon in ground vehicles for road intersections in the presence of road-side buildings. If zones are prioritized and the intersections are given greater priority, then the degree of connectivity will increase significantly.

2) UVAR-AN INTERSECTION UAV-ASSISTED VANET ROUTING PROTOCOL

Oubbati *et al.* [60] presented a UVAR routing protocol for UAV-aided VANET scenarios. The protocol implements routing decisions based on the degree of connectivity of road segments. The degree of connectivity of road segments is calculated based on the vehicular density and connectivity of the segments. UAVs gather hello packets from the vehicles and calculate the connectivity. In the case of a disconnection, the protocol utilizes UAVs as relay nodes. Every UAV calculates a connectedness score and then shares this information as hello messages. The neighbor table of a node gets updated every time a new node exchanges a hello message with the node. The host node calculates the geolocation of the neighbor node based on the table. The connectedness of a road segment is then calculated based on the derived value. Connectivity of a segment is derived using the following equation:

$$Connectivity = \prod_{i=0}^{N} \left\lfloor \frac{Range_{communication}}{(PointX_{i+1} - PointX_i)} \right\rfloor \quad (5)$$

where N denotes the total number of vehicles in the road segments, and $PointX_i$ is the x coordinate of any node. If the degree of connectivity is greater than zero, then the segment is connected and selected for the calculating process. The derived connectivity value and standard deviation of the vehicles in the segment are used to calculate the degree. Fig. 5 demonstrates the drone assistance for intravehicular communication in a sparse road segment. In the figure, the road segment is divided into multiple areas. Intersections are identified with yellow labels.
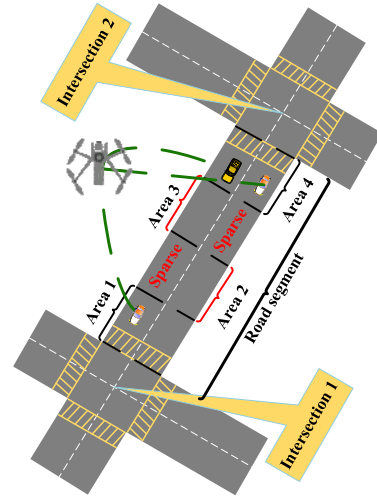

FIGURE 5. An example of area-based road segmentations.

When the data packet reaches an intersection, the carrier vehicle implements the routing decision from the shared degree of connectivity table. If the highest degree is found in another segment, then the UAVs carry the data to the enlisted connected segment.

a: ADVANTAGES

Careful consideration is given to intersections, which is a practical approach for increasing connectivity among road segments.

b: DISADVANTAGES

The mobility model for UAVs is not well-described. A global shared centralized mobility model can achieve path optimization for the SCF approach. The protocol does not allow UAV to UAV communication. In a truly sparse network, all four segments of a road can be disconnected. This causes additional energy consumptions and data delivery delay.

c: APPLICATION AREAS

This protocol gives the best output in city areas, especially in residential areas where roads are generally divided into multiple blocks/segments.

d: FUTURE IMPROVEMENTS

The vehicle can be given SCF ability to carry data towards connected zones in the case of the unavailability of the UAVs. Direction analysis can be performed for the vehicles and the UAVs. Therefore, the UAVs can carry data from multiple sources towards the same destination.

3) EXTENDED UAV-ASSISTED VANET ROUTING PROTOCOL (EUVAR)

Oubatti *et al.* [61] presented EUVAR as an extension of their previous UAV-aided VANET routing protocol, UVAR. The new version is divided into two components; namely, UVAR-G and UVAR-S. UVAR-G is dedicated to routing the data among the ground vehicles and UVAR-S is used for the

aerial network. The authors aimed to achieve improved packet delivery ratio (PDR), minimal overhead, and reduced end-to-end delay using the upgraded routing protocol. Between these two components, the UVAR-G uses a location service called grid location service (G-LS). UVAR-G implements the routing decision in three different steps. Firstly, the component calculates the traffic density. Secondly, it measures the degree of connectivity, and finally, depending on the two aforementioned calculations, it selects the appropriate road segments to route the packet. Traffic density is calculated based on the standard deviation of the vehicle on the road. A score is derived for every segment using the following equation:

$$Score_g = \delta \times \left(\frac{R_v}{(1+\sigma) \times D_w} \right), \tag{6}$$

where $Score_g$ is the connectivity score of the ground vehicle used in UVAR-G, δ denotes the connectedness, σ is the standard deviation, R_v represents the transmission range and D_w is the shortest road segment between the source and the destination. The UAV exchanges hello messages with the ground vehicles to obtain a global vision of the traffic condition. It forms a density table and shares it with the ground vehicles. If the roads are disconnected UVAR-G first attempts to find another connected segment. If it does not find any other connected segments, it exploits the UVAR-S component and even if the aerial vehicles are not available, the carrier vehicle then acts as a store carry forward node. For the UVAR-S protocol, the aerial vehicle floods RREQ packets to discover the network. When the destination UAV receives the RREQ packets from multiple sources, it picks the RREQ packet with the shortest distance and replies with an RREP packet. UVAR-S is a fault-tolerant routing component. In the case of a disconnection, the process selects an alternate route.

Fig. 6 shows the fault tolerance characteristic of EUVAR. As illustrated in the figure, UAV1 attempts to send its packet to UAV2. However, due to the broken connection, UAV1 routes the data packet towards UAV3 as an alternate route. If any node encounters any network disruption, it generates a RERR packet and redirects it to the source to reinitiate the route discovery process.

a: ADVANTAGES
Multiple recovery processes are implemented in the protocol. These recovery processes make the protocol more robust and have a positive impact on the PDR test in the simulation result. In UVAR-S, a broadcast storm is prevented to optimize the bandwidth of the network. The routing protocols exploit UAVs in both UVAR-S and UVAR-G components.

b: DISADVANTAGES
The protocol considers the same communication range for both UAVs and ground vehicles. The UAVs must have a better communication range compared to the ground vehicles because they need to contact each other and the distance
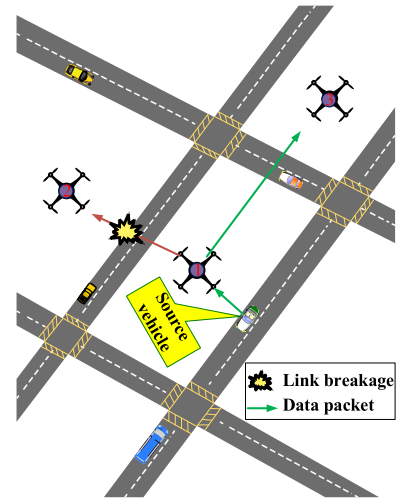

FIGURE 6. Routing through an alternate path in an aerial subnetwork.

between the UAVs is greater than the distance between the ground vehicles. UAVs are assumed to be in the middle of the four road segments, which raise the possibility of NLOS among them due to the presence of high-rise roadside building. On the other hand, the more powerful antennas will consume more power and UAVs are power constrained aerial nodes.

c: APPLICATION AREAS
EUVAR is suitable for urban areas where most of the roads are one-way. With multiple recovery options, this protocol is also suited to any sparse road.

d: FUTURE IMPROVEMENTS
Given that the roads are assumed to be straight in the simulation, the best possible location of the UAVs is above the intersections points of the roads, so that it will have more LOS possibilities compared to the presented situation in the protocol. In the simulation, the roads are assumed to be two-way roads. The end-to-end delay is adversely affected if any vehicle selects a vehicle from the opposite direction as the next hop. The direction should be considered in the future version of EUVAR.

C. POSITION-BASED ROUTING
This type of routing protocol uses geographical coordinates to route the data packets towards the destination. The vehicles gather their coordinates using GPS and share it with their neighbors. They also maintain a coordinate table of their neighbors.

1) INFRASTRUCTURE-LESS DRONE BASED VEHICULAR NETWORK ROUTING PROTOCOL (VDNET)
Wang *et al.* [62] proposed the infrastructure-less routing protocol VDNET that uses a vehicle's geographic position for data transmission. The vehicles also possess one on-board UAV to communicate with other drones and for
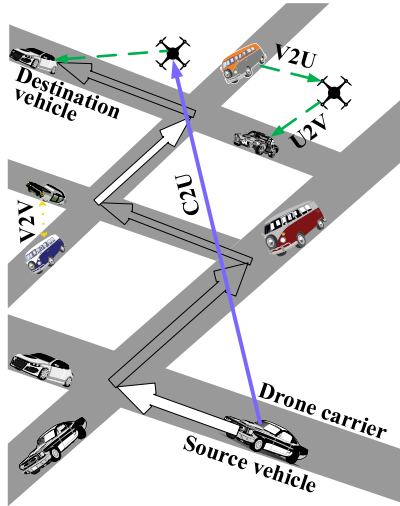
FIGURE 7. Data offloading mechanism in VDNET.

collecting geographic information about another vehicle. Fig. 7 shows the drone dispatching mechanism of VDNET to offload data directly to the destination vehicle. Later, the carrier vehicle travels to the deployed intersection to collect the drone. The figure also illustrates the carrier to UAV (C2U), V2U, U2V, V2V communication used in VDNET.

Apart from the distributed location database service, the routing protocol also uses a one-vehicle location prediction algorithm to increase the efficiency of next-hop selection and drone scheduling. Vehicles that are considered in the system update their location in the database. They also have the ability to communicate within a short-range. Each entry of the location information in the database contains the vehicle id, location, direction, velocity, refresh time, and received time. If a vehicle's local database does not contain the destination vehicle's entry, then it goes into a passive mode and waits for the vehicle to appear on the list. Instead of copying the entire database to the neighbor, VDNET only contributes to its neighbor routing process, which is known as compare-and-exchange. The preferred location for advanced location prediction is divided into the area, route, and isolated places. Advance location prediction calculates the probability for both visited and non-visited places. The probability of the visited places can be obtained using the following formula:

$$P_{close}(L = \iota_i)_{\iota_i \in k_i^{(c)}} = \frac{\left| k_i^{(c)} \right|}{\sum_{m=1}^{|M|} \left| k_m^{|M|} \right| + 2 \sum_{n=1}^{|N|} \left| k_n^{(N)} \right|} \quad (7)$$

where P_{close} is the probability of the already visited location, c denotes the category, M is the area, N represents the routes, and k indicates the preferred regions. The probability of the closed observation is zero when the place ι_i is not listed in the local database.

a: ADVANTAGES

Given that the protocol uses drones to deliver messages to other vehicles, the chance of bandwidth congestion is less in this system. The compare-and-exchange mechanism significantly reduces overhead. The advance location prediction is divided into known and unknown places. Furthermore, the prediction mechanism also attempts to determine the position of a node on a devised vector. This method requires less time and has better efficiency.

b: DISADVANTAGES

If the UAVs do not follow one combined path planning, they may collide with each other. According to the procedure, if the destination vehicle is not in the location databases of the source vehicle database, as stipulated in the routing procedure, the vehicles enter a passive mode and wait for vehicles to appear on the list. However, data from multiple nodes causes significant buffer issues.

c: APPLICATION AREAS

This protocol is mostly applicable to infrastructure-less areas where the GPS is operational and the density of the drone-carrying-vehicle is not high.

d: FUTURE IMPROVEMENTS

The drone only serves its parent vehicle. If it can carry the data of other vehicles in its flight direction, this could lead to UAV number optimization.

2) DELAY CONSTRAINED UAV-VANET ROUTING PROTOCOL (DURP)

Zeng *et al.* [63] proposed DURP, a routing protocol for the UAV-aided VANET system. For enhanced vehicle mobility prediction, the protocol uses a recursive least square (RLS) algorithm. DURP also uses a maximum vehicle coverage (MVC) algorithm to schedule the movement of the UAV during data transmission. One control server is exploited for the channel prediction based on the information supplied by the vehicles. The UAVs download data and dispatches to the vehicles while flying above the roads. All the moving nodes in the system are equipped with GPS receivers. Using the GPS, the receiver nodes gather the necessary information such as direction, speed, position, etc. A backbone link connects the central server (CS) to all the RSUs. The CS runs the scheduling algorithm based on the information collected by the node and again dispatches in the same manner. Fig. 8 shows the network paradigm for the routing protocol DURP.

In Fig. 8, the server (CS) is connected to the RSUs. The figure also illustrates the bi-directional command passing mechanism from the CS to the RSUs, RSUs to UAV and vehicles, UAV to the vehicle, and inter-vehicle communication. The data collection takes place in the T1 phase whereas the scheduling and command dispatching occurs in the T2 phase. This is based on the current speed, position, the direction the CS selects for the UAV's next destination speed, and the
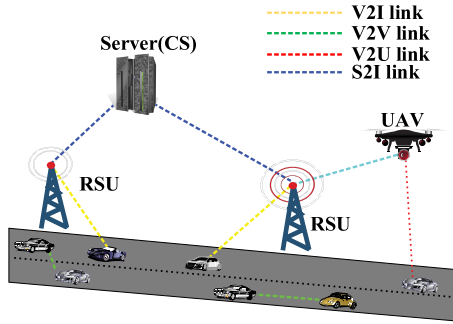
FIGURE 8. Visualization of the communication mechanism including the central server.

relay node to transmit data. In the last phase, the commands are relayed according to the instructions given by the CS. The CS schedules the data transmission and position of the nodes based on channel prediction. It maintains the following condition to generate the next command:

$$\begin{cases} \left(\bar{X}_{ui} - X_{ui}\right)^2 + \left(\bar{Y}_{ui} - Y_{ui}\right)^2 \leq (V_{MAX}\Delta t)^2 \\ |\bar{\alpha}_{ui} - \alpha_{ui}| < \alpha_{max}\Delta t \end{cases} \quad (8)$$

where the maximum speed of the UAV is denoted as V_{MAX}, the time difference is Δt, the coordinate of the new location is $(\bar{X}_{ui}, \bar{Y}_{ui})$, the coordinate of the old location is (X_{ui}, Y_{ui}), and the previous and present azimuth angular speeds are $(\alpha_{ui}, \bar{\alpha}_{ui})$ and the maximum angular change is $\alpha_{max}\Delta t$.

a: ADVANTAGES
This protocol uses the CS to increase the overall efficiency given that all the nodes can behave in unison. For A2G or G2A communication, this routing algorithm considers LOS and NLOS that also increases the efficacy.

b: DISADVANTAGES
The main disadvantage of a centralized protocol is the single point of failure. If the CS is compromised for any reason, the entire system is affected. The protocol assumes that every node is connected at all times, which can be used to convey commands from the CS without any delay. However, without distributed pathfinding capability the UAV nodes will likely cause an extra delay with random mobility. If an intruder hacks the CS, access to the entire network is obtained. As such, this protocol is more vulnerable.

c: APPLICATION AREA
This protocol requires a secure and well-developed urban area for full operation.

d: FUTURE IMPROVEMENTS
The algorithm should introduce a regular RSU visiting system for the UAVs if it does not receive any instructions for a specific time period. In a more advanced system, vehicular density prediction along the road segment can be introduced.

D. DTN-BASED ROUTING
This type of routing is applicable to sparse networks, where UAVs are used as SCF nodes to deliver data towards the destination.

1) DRONE BASED HIGHWAY VANET ROUTING PROTOCOL (DBVP)
Selim *et al.* [64] proposed a UAV-aided VANET routing protocol named DBVP. This protocol aims to achieve a minimum packet delivery delay by considering a two-way highway scenario. To estimate the minimum number of drones with a delay threshold limit, DBVP utilizes a closed-form expression. The number of road segments and vehicles on a highway is assumed to be a Poisson distribution. According to the protocol a source vehicle sends its generated message in the opposite direction to increase the probability of the vehicle to drone packet delivery ratio. The algorithm also considers "times" as a parameter to calculate vehicular densities. To calculate the maximum distance between two nodes, DBVP uses the closed-form expression with predefined delay constraints, vehicular density, and the vehicle's exiting prediction through any junctions. The problem of the closed-form expression can be stated as below:

$$\begin{aligned} &\text{maximize } a \\ &\text{subject to } 1 - F_T\left(T_{max}, a\right) \leq \epsilon \end{aligned} \quad (9)$$

where the number of drones is denoted as a, the delay constraint is represented by T_{max}, and the violation probability is assumed to be ϵ. Based on the obtained result, DBVP switches the required number of UAVs on or off. The protocol determines which drones should be turned on or off based on its charge condition. If all the drones contain the same amount of charge, then the drones near the end of the highway will be turned off first.

a: ADVANTAGES
The closed-form expression used in the routing protocol DBVP can determine the maximum separation distance from one UAV to another that achieves optimization of the number of UAVs. A two-way highway road scenario is a practical approach to achieve maximum connectivity.

b: DISADVANTAGES
According to the proposed routing system the vehicle can also deliver the data to the vehicles coming from the opposite direction. However, in ITS application, the amount of data that the vehicle intends to transfer might be too large compared to the available time for the transfer window.

c: APPLICATION AREAS
Branchless long highways are best for implementing this routing protocol.
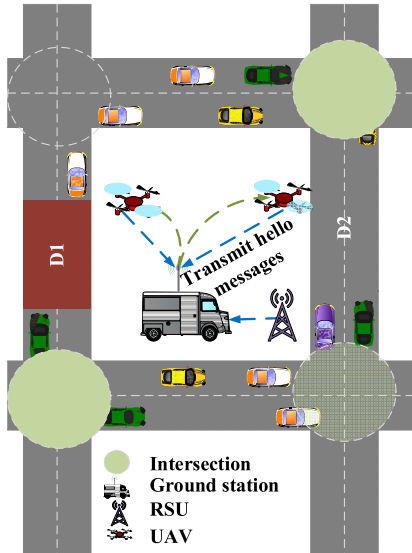
FIGURE 9. Reporting mechanism of disconnected segments from UAV to ground stations.

d: FUTURE IMPROVEMENTS

The protocol assumes a constant bit rate pattern between a drone and a vehicle. However, in practice, the bit rate varies depending on environmental variables, channel interference, channel fading, etc. To facilitate a superior outcome in the future, the protocol should consider the aforementioned fact.

2) LIGHTWEIGHT AND EFFICIENT ROUTING PROTOCOL FOR UAV-AIDED VANET (LEUV)

Sedjelmaci *et al.* [65] presented a game-theory-based UAV-aided VANET routing protocol referred to as LEUV. The protocol attempts to reduce the energy consumption of UAVs by preventing broadcasts storms. LEUV can also predict the disconnected segments and characterizes specialized channels for UAVs. The ground station first collects the traffic condition using hello messages sent from the UAV. UAVs are then launched from ground vehicles to observe the road condition.

Fig. 9 shows the underlying architecture of the communication model used in LEUV. In the figure, the UAVs fly over the disconnected D1 and D2 zones and exchange hello messages with the ground station. The figure also shows the connection between the ground station RSU, and the UAVs. Optimal locations for ground stations can be determined based on a graph-based model in regions where the number of vehicles is low. The ground vehicles can communicate with each other using professional digital radios such as TETRAPOL. The prediction game is designed to achieve network optimization such as low end-to-end delay and low battery consumption of the UAV.

The payoff function increases when the ground station successfully predicts the disconnected segments; otherwise, it decreases if a UAV flies over a connected segment or no UAVs fly over a disconnected segment.

Another game is developed to minimize the overhead of the UAV. The gain function of the second game is given as follows:

$$G_{total} = \sum_{j\in\{1,\dots,N\}} O_{u_{ij}} \qquad (10)$$

where G_{total} is the amount of overhead generated by the hello messages of the vehicles and the amount of overhead for the UAV u_i to the vehicle, j is represented as $O_{u_{ij}}$. The number of packets in a single UAV is derived using the following equation:

$$O_{u_i} = \alpha t_{u_i} + \beta e_{ui} \qquad (11)$$

where t is the transmission time that is calculated based on the number of packets received and data rate, and e is the energy consumption rate. The parameter u_i represents the energy consumption associated with the received messages in each period. The variables α, β represent the weighting parameters of the transmission time and energy consumption, respectively. The game attempts to establish the Nash equilibrium between the number of UAVs and the accuracy of the prediction.

a: ADVANTAGES

Two-way communication model requires less energy. The game theory approach for broadcast mitigation also reduces the energy consumption of the UAV. These energy optimization techniques result in an increase in the hovering time of UAVs. The use of ground vehicles reduces the lying range of the UAV, which also conserves a significant amount of energy.

b: DISADVANTAGES

The use of ground stations as mobile infrastructure can be problematic to implement in a disaster area. These vehicles require a minimum ground way condition to travel to a specific destination. Roads can be easily compromised due to natural or man-made disasters.

c: APPLICATION AREAS

Effective for disaster area whereby the roads are in adequate condition to support the transporting vehicle.

d: FUTURE IMPROVEMENTS

On-air command passing technique from the ground vehicle to UAVs will reduce their flying path. As a result, energy consumption will be further reduced.

3) MULTI PHASED UAV-AIDED VANET ROUTING PROTOCOL (MPUVP)

Zhou *et al.* [66] proposed a topology-based routing protocol with DTN support. The routing protocol emphasized effective UAV scheduling and adaptive formation planning for enhanced connectivity and energy-efficient networking. The network is organized into two layers. One of them is the aerial network that consists of the UAVs and the other is the ground network that consists of the ground vehicles. The network
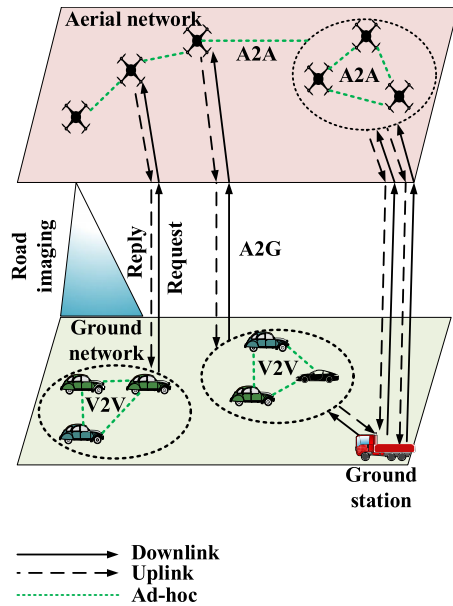

FIGURE 10. Various communication types in the MPUVP routing protocol.

also utilizes three different types of system components: UAV, ground vehicle and ground stations. At the beginning of the routing process, the ground station dispatches two scout UAVs to gather information about the overall situation in the area of interest. Depending on the gathered information, the ground station determines the number of UAVs required to form a multi-hop network. In addition, the ground station also determined the formation of the aerial network. Fig. 10 illustrates the different data communication models, UAV clustering, vehicle clustering, and road imaging techniques used in MPUVP. The authors have shown that a better formation of the aerial network has a positive impact on data latency, and end-to-end delivery in the multi-hop approach. To determine the road condition, the UAVs acquire images of the road from the deployed area. Before transmitting the raw images to the ground station, the UAV compresses the image to optimize bandwidth usage. In a multi-hop approach, this processed data is then transmitted to the ground station for further processing. After the road condition is determined from the received image, the ground station broadcasts the information to the ground vehicles via V2V networks. A disconnection is possible at any moment due to a variety of reasons. When an aerial vehicle detects a disconnection, the UAV changes its role from a multi-hop node to an SCF node until it finds the next hop. Occasionally, UAVs may operate in a low battery mode and request that the ground network should returns. In these cases, the ground station informs the UAV of the status of the charging station. In addition, the ground station can utilize any idle UAVs to fill any blank spaces. If idle UAVs are unavailable, then the aerial node shifts its role again from multi-hop to carry-forwarder. If any changes to the ground or aerial vehicle occur, the ground station is aware of the UAVs or ground vehicles via the G2A or V2V network.

a: ADVANTAGES

This proposal fully exploits the ground station in terms of communication and vehicle management. The ground station is also used to extract information from an image, which is a resource-intensive process. All the scheduling plans are performed in the ground stations which conserves the energy of the mobile vehicle. The instant role changing mechanism of the network also facilitates better connectivity. The proposed system also attempts to optimize energy usage by optimizing the UAV's posture, altitude, hovering system, etc.

b: DISADVANTAGES

The processing of images using the OBU of the UAV consumes a lot of energy and requires significant processing power. Thus, this is not a suitable option for quadcopters.

c: APPLICATION AREAS

This protocol is suitable for disaster-affected open road areas, where UAVs can use imaging techniques to scout the road condition and transmit information to a central server.

d: FUTURE IMPROVEMENTS

The ground station plays a core role in the routing system. Therefore, the placement of this station in an optimal position will result in better outcomes. Charging stations are an essential component of non-self-energy-harvesting UAVs.

E. SECURITY-BASED ROUTING

In security-based routing, different types of security analyses are performed in the routing process to keep the network safe from malicious nodes. UAVs are utilized to analyze security threats. In addition, they assist with other data routing processes.

1) ANTI-SMART JAMMING WITH REINFORCEMENT ROUTING PROTOCOL (ASJRL)

Xiao et al. [67] presented the ASJRL routing protocol with the objective of increasing the security against smart jammers in a UAV-aided VANET system. A game is formed based on the iterative action between the UAV and the smart jammer to determine the conditions of the Nash equilibria. In addition, the protocol utilizes the policy hill-climbing algorithm to enable the UAV to take more random action against the jammer. Random actions of the UAV can deceive the jammer. As a result, transmission security is not breached.

As shown in Fig. 11 the OBU_3 of a vehicle transmits data to the server with the assistance of RSU_1. The data are received by both RSU_1 and the UAV. The jammer in the network can redirect the data in the wrong direction. Therefore, the UAV further examines the data before transmitting it to RSU_2. Thus, RSU_2 is more secure due to data filtration of the UAV. To verify the authenticity of the received message sent from the OBU, the UAV determines the system state of the network.
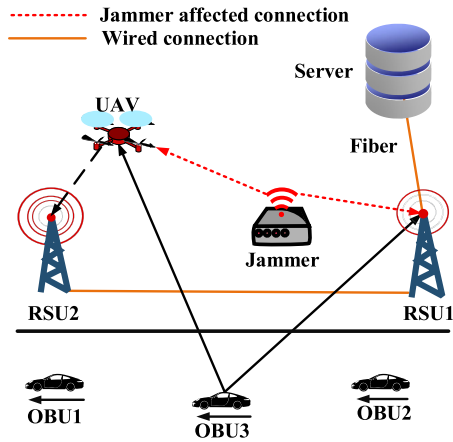
FIGURE 11. Data routing in the presence of a jammer.

The system state is obtained using the following equation:

$$S^{(k)} = \left[\rho_1^{(k-1)}, \rho_2^{(k-1)}, \rho_3^{(k-1)}, P_e^{(k-1)} \right] \quad (12)$$

and

$$P_e^{(k)} = \min \left(P_e \left(\rho_1^{(k)} \right), P_e \left(\rho_2^{(k)}, \rho_3^{(k)} \right) \right) \quad (13)$$

where the system state at the kth time is denoted by $s^{(k)}$. The system state contains information on the link quality between the UAV and the OBU, which is denoted as ρ_1; the link quality between RSU and the OBU is expressed as ρ_2; the signal to interference plus noise (SINR) between RSU_2 and the UAV is denoted by ρ_3, and the bit error rate (BER) is expressed as P_e of the received message at the previous time slot (k-1). Given that communication behavior can be modeled as a Markov decision process (MDP), reinforcement learning is applied for future decision-making processes. Reinforcement learning procedures use one Q-function along with a value function to maximize efficiency.

a: ADVANTAGES

ASJRL increases the overall security of the network. The protocol considers the speed of the OBU and is, therefore, more suitable for real-life implementation. The use of the RL technique saves time because the next step is not chosen by redundant random exploration.

b: DISADVANTAGES

The routing protocol only filters messages for the UAV's end. As such, other terminals are vulnerable to threats such as OBUs and RSUs. According to the protocol, the OBUs redirect their message towards the RSU, as well as the UAV. However, if the data packets are specialized for the RSU and the UAV, then the intended destination could be easily identified. The data-driven approach is not suitable for UAVs because of its energy and computational limitation.

c: APPLICATION AREAS

This routing protocol is suitable for urban areas where a large amount of data traffic is generated by vehicles, and for sensitive locations that are vulnerable to jammers.

d: FUTURE IMPROVEMENTS

A recovery option should be introduced if the UAV detects the presence of a jammer in the network by analyzing the packets. A more complex jamming model should be introduced to the paradigm to improve its robustness as a secured routing protocol.

2) TRUST-BASED UAV-AIDED VANET ROUTING PROTOCOL (TURP)

Kerache *et al.* [68] proposed a UAV-aided VANET routing protocol named TURP. The protocol detects malicious nodes, prevents them from further routing and assists trusted authority in acting against such selfish nodes. The routing protocol involves the use of UAVs to detect abnormal behavior of the nodes and to relay black-listed nodes to the RSU. Firstly, the drone divides the ground vehicles into groups and forms clusters. To conserve energy, the drone selects one cluster head from each cluster. The cluster member with the minimum distance from the center of the cluster is initially selected as the cluster head. Although this type of cluster head selection might result in a malicious node being chosen as a cluster head, the probability decreases after the second iteration. In the second iteration, the drone selects a cluster head based on both the rust score and the closeness of the node to the control point. Scoring for the selection of the cluster head is achieved using the following equation:

$$Score\,(ID) = Max \frac{Trust\,(TA, ID)}{Distance(P\_ID, Central\_point)} \quad (14)$$

where *ID* is the vehicle's unique number, *TA* represents the trust authority, *P_ID* is the vehicle's unique id, and *Central_point* is the central point of the ground vehicle clusters. UAVs communicate with each other such that the same vehicle is not considered. Trust is calculated locally by the cluster head, and globally by the trust authorities (TAs). Trust calculation depends on the direct and indirect opinion regarding a vehicle. The opinion is added as extra three-byte data with the data packet. Two bytes are allocated for the neighbor ID and one byte is used for the opinion. Trust scoring is an adaptive feature. The score of a vehicle can be degraded and upgraded with time. If a vehicle's score is below the threshold limit, the vehicle will be disabled from packet transmission.

a: ADVANTAGES

Bandwidth optimization is one of the most effective features of TURP. The opinion does not add too much extra information with the beacon message. Clustering the ground vehicle is also one type of bandwidth optimization.
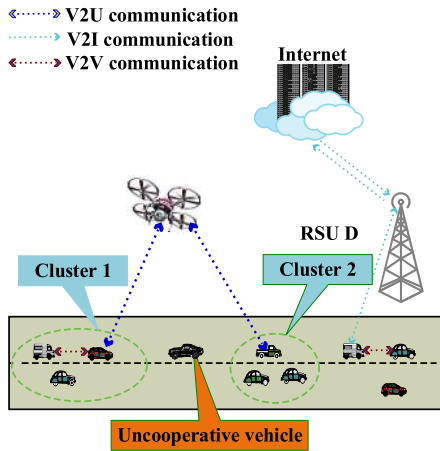
FIGURE 12. Routing in the presence of a selfish node.

b: DISADVANTAGES
TA based evaluation services introduce additional costs to the overall system.

c: APPLICATION AREAS
This protocol is applicable to vulnerable urban areas where the chance of an attack is significant.

d: FUTURE IMPROVEMENTS
A small number of punishing capabilities in the UAV will allow the protocol to implement faster responses against malicious nodes.

F. CLUSTERING-BASED ROUTING
In clustering-based routing, clusters are formed among the vehicles to optimize the usage of UAVs in data routing processes. Aggregated data are sent to the UAVs to minimize the transmission counts. Vehicles can communicate freely within clusters with a low end-to-end delay.

1) UAV-BASED VANET ROUTING PROTOCOL FOR NON-COOPERATIVE NETWORK (UVPN)
Fawaz [69] presented the URPN routing protocol for the non-cooperative UAV-aided VANET network. URPN analyses the negative impacts of a non-cooperative vehicle in the network. The routing protocol also applies various techniques to mitigate the adverse effect of a non-cooperative vehicle in the network, using the UAVS as a SCF node. In the VANET system, a vehicle can enjoy ITS services when it is in the range of the RSU or the vehicle can exchange data with the help of other vehicles in a multi-hop manner. Path discontinuity can occur in the presence of a malicious node or due to the lack of common nodes between two clusters. Both issues are depicted in Fig. 12.

According to Fig. 12, the communication between cluster1 and cluster2 is hindered due to the presence of the uncooperative vehicle and the UAV is used to re-establish the connection between them. If the destination vehicle is not

inside the communication range of the UAV, it changes its role and operates as a store carry forward node. The protocol utilizes two different communication channels; namely, the control channel (CCH) and the service channel (SCH). To establish a communication channel, a node uses CCH whereas SCH is used to exchange other data packets. Two UAVs are considered to fly in the opposite direction of a road segment to facilitate disruption-free connectivity. Path availability is formulated using the equation given below:

$$P_{sd} = (1 - P_e) \left\lceil \frac{d_{sd} - R}{W} \right\rceil \tag{15}$$

where P_{sd} stands for path availability, $(1 - P_e)$ is the probability of one-hop packet transmission, d_{sd} denotes the distance between vehicle S and D, R represents the communication range and W is the mean intra-cluster distance in the presence of the UAV.

a: ADVANTAGES
Two drones flying in the opposite direction facilitate continuous connectivity on the vehicles from both directions. The protocol calculates path connectivity based on the vehicle's speed, co-operative vehicle probability, and density, which makes the protocol more robust.

b: DISADVANTAGES
According to the protocol two UAVs fly in the opposite direction to provide connectivity support to the vehicles. However, when the UAVs cross each other, their communication range overlap, and the aggregated range decreases. This kind of modeling is also a reason for the extra energy consumption of the UAV.

c: APPLICATION AREAS
Mostly suitable for two-way urban areas where the number of infrastructures is relatively low.

d: FUTURE IMPROVEMENTS
Malicious node can have effects other than non-cooperation of the transmission process. The proposed protocol should consider other malicious activities to ensure better end-to-end connectivity and delay.

2) UAV-BASED STORE CARRY FORWARD ROUTING PROTOCOL (USCF)
Fawaz *et al.* [70] proposed the USCF routing protocol for a UAV-aided VANET system. The protocol exploits UAVs as SCF nodes with the aim of improving the end-to-end connectivity and decreasing the delivery delay. According to the protocol, the vehicles form clusters. In a cluster, the data can flow freely using V2V connections. The routing of data to the RSU is only possible when a member of the cluster has a direct connection with the RSU or the data can be propagated between clusters in a multi-hop manner. Disconnections between clusters are addressed using UAVs. The UAVs are divided into two groups, and one group flies in the

opposite direction to the other group. The main goal of this direction-based approach is to facilitate the enhanced connectivity of vehicles traveling in the same direction. The speed of the UAVs is optimized to 50 ms^{-1} to maintain the connection for the required period. Inter-cluster communication is possible if the rightmost vehicle of cluster1 can communicate with the UAV and if the leftmost vehicle of cluster2 is within the communication range of the UAV. If there are no vehicles from any other cluster, then the UAV shifts its role to the SCF mode. Given that UAVs constantly fly above the road segments, the connectivity improves significantly. For the delay analysis, the author divided the delay into two parts that carry the delay and the communication delay. Given that the carry delay is significantly larger than the communication delay, only the carry delay is considered for the delay analysis. The average carry delay can be derived using the following equation:

$$E\left[T'\right] = \frac{E\left[d'\right]}{E\left[V'\right]}, \tag{16}$$

where $E\left[T'\right]$ is the average carry delay, $E\left[d'\right]$ denotes the carry distance, and $E\left[V'\right]$ represents the space mean speed. To calculate the carry distance, the Poisson vehicle arrival process and periodic UAV arrival process are taken into consideration.

a: ADVANTAGES

USCF maintains an optimized constant UAV speed that assists the UAV in maintaining communication with the vehicle for a longer time period. In this routing model, the UAVs maintain a fix communication distance that facilitates greater coverage of the entire aerial network. UAVs only communicate with vehicles that travel in the same direction that allow sufficient time to exchange data.

b: DISADVANTAGES

UAVs are assumed to be solar-charged but this type of modeling renders UAVs as inappropriate for nighttime hovering.

c: APPLICATION AREAS

Well-infrastructured urban areas with less complicated road structure.

d: FUTURE IMPROVEMENTS

The protocol assumes the best case for RSU placement, which can lead to undesirable outcomes in real-life implementation.

3) VANET ROUTING WITH UAV ASSISTANCE (VRUA)

Khabbaz *et al.* [71] presented a UAV-aided VANET routing protocol called VRUA. This protocol attempts to increase the throughput of a network and decrease the end-to-end packet delivery by supporting weak links with the assistance of a UAV. The protocol utilizes a customized mobility model for UAVs. Ground vehicles form clusters. Cluster members communicate with each other without any disruptions. UAVs

relay data between two disconnected clusters. If the distance between two clusters is too large, the UAV goes back and forth between them and operates as a store carry forwarding node. The number of drones required is determined using the following equation:

$$kR_u < \delta_{ij} \le (k+1)R_u \, (k \in N), \tag{17}$$

where R_u is the transmission range of the UAV, k is the number of UAVs, δ_{ij} denotes the distance between the ground node i and the ground node j, and R_v represents their communication range. The ground nodes are connected and can facilitate communication between them when $\delta_{ij} \le R_v$. If $\delta_{ij} < 2R_u$, then one UAV is used to rebuild the communication link. When $\delta_{ij} > 2R_u$ then the second UAV is utilized and a UAV to UAV communication link is built between them. VRUA is a DTN supported protocol. If a sufficiently large number of drones are not available, then the UAVs can act as an SCF node.

a: ADVANTAGES

VRUA uses multiple channels that reduce the chance of inference. As a result, the overall packet delivery ratio (PDR) is improved. The route planning algorithm for the UAV plays a significant role in terms of the UAV's visit optimization in the disconnected zones.

b: DISADVANTAGES

The protocol does not consider multiple segment coverage. The communication ability of drones can support multiple edges and this type of characterization is important in the design of a robust protocol.

c: APPLICATION AREAS

Custom path planning assists VRUA in covering geographically complex urban road layouts.

d: FUTURE IMPROVEMENTS

Along with the path planning, segment division with a scoring system can improve performance. In addition, the relative speed difference between the UAV and the vehicle support for large ITS data transformation is necessary for further improvement.

G. SDN-BASED ROUTING

Software-defined networking (SDN) separates the control panel from the data forwarding panel [72]. It has numerous advantages compared to traditional networking systems. Network management, deployment of security policies, scaling up or down, and troubleshooting is some of the major benefits of this network paradigm. The network architecture is logically centralized. As such, the SDN can acquire information on the entire routing condition. It enables the controller to implement improved routing decisions that are beneficial to highly mobile networking scenarios such as VANET.

TABLE 2. Special features of the existing routing protocols for UAV-aided VANETs.

Protocol	Reference	Special feature
DCUVP	[55]	Link scoring based on link delay and transmission rate
CRUV	[56]	Segment density calculation based on the vehicles to turn left and right for selecting the best intersection
GACP	[57]	Characterization of LOS based on the road layout
ZRPUV	[59]	Effective path expiration time calculation
UVAR	[60]	Special consideration of the road segment intersection and global and local segment scoring
EUVAR	[61]	Multiple recovery policy and different routing components for ground and aerial nodes
VDNET	[62]	Fully infrastructure-less operation and onboard UAV-carrying-vehicle
DURP	[63]	Use of a central controlling system for UAV scheduling
DBVP	[64]	Information replication by transmitting data to the vehicle in the opposite direction
LEUV	[65]	Multiple energy optimization techniques
MPUVP	[66]	Use of scout UAVs to predetermine road condition
ASJRL	[67]	Adaptive jammer power prediction technique
TURP	[68]	Trust-based malicious node selection
UVPN	[69]	Consideration of vehicles' variable speed in the path availability calculation
USCF	[70]	UAVs only transmit data to the vehicle in the same direction.
VRUA	[71]	Special mobility model for UAVs
SURP	[73]	Energy optimization technique by distributed computation based on complexity
RPUBN	[58]	Implementation of CDS-based UAV backbone network

1) SOFTWARE-DEFINED UAV-AIDED VANET ROUTING PROTOCOL (SURP)

Alioua *et al.* [73] proposed the SURP routing protocol for the UAV-aided VANET architecture. SURP is a specialized routing protocol for an infrastructure-less software-defined distributed networking paradigm. The routing protocol utilizes game-theory techniques to implement data offloading decisions to minimize the energy consumption of the UAVs.

Three different tuples G (N, A, μ) is used to design the game. N denotes either the aerial vehicle or the ground vehicle, A is the decision parameter that denotes the local computation or the ground vehicle's computation, and the payoff function for each player is expressed as μ. The global payoff function that denotes the data computation cost of the system is represented by the following equation:

$$P_i(t) = \mu_i(t) = \mu_{1,i}(h_{1,i}) + \mu_{2,i}(h_{2,i}), \qquad (18)$$

where i is the computation task at time slot t; h_1 and h_2 are the strategies and μ_1 and μ_2 are the payoff function for player one and two, respectively. The control plane layer has three different types of nodes. Among them, the local controller is a ground vehicle that maintains a V2V communication with other ground vehicles and can be utilized for medium complex level calculations. The primary controller is also a ground vehicle that communicates with both the aerial node and the ground nodes, whereas the secondary controller is an aerial node with medium computation level capability. The secondary controller maintains communication with the primary controller and the forwarding of the UAVs. The UAVs are used to collect data such as videos and images of the roads, to assist emergency vehicles. The emergency vehicles possess an onboard UAV to examine the road and traffic condition. UAV collected data can be processed locally by the secondary controller in the air or the raw data can be transmitted via a Wi-Fi connection to the ground controller. The length of the road segmentation is fixed as half of the communication range of the IEEE 802.11p. Using this approach, the vehicles can communicate with other vehicles in adjacent segments because they use IEEE 802.11p as their niche communication protocol. In each segmentation, a dedicated vehicle is selected as the local controller that is responsible for the calculation and aggregation of the local data transmitted by the vehicles in the same segmentation.

a: ADVANTAGES
Inclusion of software-defined networking in UAV-aided VANET is a good approach for optimization of the UAV's energy.

b: DISADVANTAGES
Not applicable for sparse vehicular network conditions. Both aerial and ground vehicles require specialized computation capability to perform specific roles and as such the protocol is difficult to implement.

c: APPLICATION AREAS
Applicable to scenarios in which the UAVs need to process data onboard so that they can assist emergency vehicles while minimizing delay.

d: FUTURE IMPROVEMENTS
The selection of the local controller can be elaborated, and the vehicle's position, direction, speed, and connectivity level should be considered.

TABLE 3. Evaluated performance metrics and performance objective of the existing routing protocols for UAV-aided VANETs.

Protocol	Reference	Evaluated performance metrics	Performance objective
DCUVP	[55]	Packet delivery ratio (PDR), throughput, and the number of hops (NOH)	Throughput maximization
CRUV	[56]	PDR, average number of hops (AOH), and end to end delay (EED)	Minimization of packet loss
ZRPUV	[59]	PDR, EED, routing overhead (RD), and AOH	Routing overhead minimization.
UVAR	[60]	PDR, EED, and AOH	Reliable data delivery
EUVAR	[61]	PDR, PDR, EED, EED, overhead, and average hops (AH)	Overhead minimization and the shortest end to end communication
VDNET	[62]	Drone owing rate and average prediction error	Minimizing EED
DURP	[63]	Data dissemination delay and system throughput	Data dissemination delay
DBVP	[64]	EED, EED, vehicle to UAV delay, and delay	Delay optimization
LEUV	[65]	Disconnected segment prediction, EED, PDR, EED, and overhead	Overhead optimization
MPUVP	[66]	Power consumption of UAV and EED	Minimization of EED
ASJRL	[67]	BER, time slot, BER, and utility of UAV	Minimization of BER
TURP	[68]	Malicious node detection ratio, malicious node detection ratio, PDR, and false-positive ratio	Detection of malicious nodes while maintaining PDR
UVPN	[69]	Path availability and EED	Maximization of path connectivity
USCF	[70]	Path availability and EED	Reducing EED
VRUA	[71]	Path availability and EED	Upgrading delay performance
SURP	[73]	Average delay, system cost, computational delay, and energy consumption	Minimization of UAV's energy.
RPUBN	[58]	PDR, EED, overhead, residual energy, the number of covered segments, the number of backbone UAVs, and travel time of UAVs	Balanced energy consumptions of UAVs

IV. COMPARISON OF THE ROUTING PROTOCOLS

In this section, the routing protocols of UAV-aided VANETs are qualitatively compared based on their innovative ideas, characteristics, extraordinary features, and optimization criteria. Table 2 summarizes the key outstanding features of the protocols. Table 3 lists the evaluated performance metrics and performance objectives of the discussed protocols. Table 4 summarizes the comparison of the protocols in terms of various parameters and factors. These three tables will help researchers and engineers to choose the most appropriate protocol or to design a new routing protocol. In the following subsection, an in-depth discussion on performance and special features is addressed. This is so useful to readers because the strength and weaknesses of the special features, as well as the performance criteria, are technically discussed.

Table 2 shows the most innovative features of the investigated protocols. It can be observed that the DTN-based protocols have the highest end-to-end delay but the lowest network congestion. In a sparse network, UAVs are used as the SCF node. However, the protocols designed for the urban environment are likely to have reduced end-to-end delay and

better connectivity for dense road conditions. A few protocols attempt to optimize the altitude of UAVs whereas others attempt to provide maximum area coverage by establishing connections with the maximum number of vehicles. However, both optimization techniques affect the stability, durability, and connection strength of links. For each protocol in Table 2, the special feature supports the performance objective.

Table 3 summarizes the evaluated performance metrics and performance objectives. As expected, the protocols having special mechanisms use more control packets, resulting in additional overhead. However, the special mechanism is directly related to the performance objective of the protocol. As a result, the performance metrics are selectively chosen and evaluated depending on the performance objective. The performance and special features of the discussed routing protocols are elaborately discussed in Section IV.A.

Table 4 presents the comparison of the reviewed protocols in terms of their optimization features for different QoS parameters, performance metrics, and techniques. However, none of the protocols exhibits UAV clustering in an aerial subnetwork. Some of them consider the energy of the UAV as

TABLE 4. Comparison of optimization criteria and technique of the routing protocols for UAV-aided VANETs.

Protocol	Year	UAV energy consideration	Optimization of the number of UAVs	Bandwidth optimization	Dependency on static infrastructure	UAV path planning	Availability of recovery process	UAV position optimization	UAV Altitude optimization	DTN support	Localization aware simulation	Consideration of UAV-to-vehicle distance	Delay constraint optimization
DCUVP	2018	x	x	x	x	x	x	x	x	x	✓	x	✓
CRUV	2016	x	x	x	x	x	✓	x	x	✓	x	✓	x
GACP	2017	✓	✓	x	x	x	x	✓	✓	x	x	✓	x
ZRPUV	2019	x	x	✓	✓	x	✓	x	x	x	✓	✓	x
UVAR	2016	x	x	x	✓	x	✓	✓	x	✓	x	x	x
EUVAR	2017	x	x	✓	✓	x	✓	x	x	✓	x	x	x
VDNet	2016	x	x	✓	x	✓	x	✓	x	✓	x	x	x
DURP	2018	x	✓	x	✓	✓	✓	✓	x	✓	x	✓	x
DBVP	2018	x	✓	x	x	✓	✓	✓	✓	✓	x	x	✓
LEUV	2018	✓	✓	✓	✓	✓	x	x	x	✓	x	x	x
MPUVP	2015	✓	x	✓	✓	✓	✓	x	✓	✓	x	x	x
ASJRL	2018	x	x	x	✓	x	x	x	x	x	x	✓	x
TURP	2018	✓	x	✓	✓	x	x	x	x	x	✓	✓	x
UVPN	2017	x	✓	x	✓	✓	x	x	x	x	x	x	x
USCF	2017	x	x	x	✓	✓	x	✓	✓	✓	x	x	x
VRUA	2019	x	✓	x	✓	✓	✓	✓	x	✓	x	✓	✓
SURP	2018	✓	✓	x	x	x	x	x	x	x	x	x	x
RPUBN	2019	✓	x	x	x	x	x	x	x	x	✓	x	x

Note: "x" means the absence of the technique and "✓" means the presence of the technique.

the major factor whereas others focus on bandwidth optimization. The protocols designed for post-disaster management generally use extra mobile infrastructures to establish temporary data offloading stations for UAVs. Disconnected location prediction techniques introduce UAV positioning techniques as relay nodes. Almost all the routing protocols use SCF to support delay tolerant networks. However, only a few present a detailed overview of the technique. The following discussion is given based on the optimization technique and criteria used in the literature. The impact of the optimization criteria and techniques on performances are elaborately discussed in Section IV.B.

A. DISCUSSION ON PERFORMANCE AND SPECIAL FEATURES

In this subsection, we discuss the performance and special features of the reviewed routing protocols in depth. That is,

the strength and weaknesses of the special features, as well as the performance criteria, are technically discussed.

DCUVP [55] adopts a link scoring technique for throughput maximization, but the outcome is not analyzed when multiple nodes evaluate the same link for data transmission. The greater number of nodes from the source to the destination with the lesser number of intermediary nodes will increase the delay. If the special capability of the UAV has not been taken into consideration, this may trigger greater delay; otherwise, the delay could have been more optimized after considering the practical scenario. This innovative feature of DCUVP will have a positive impact on throughput.

CRUV [56] selects the road segment based on the density of vehicles, which leaves a positive impact on the link continuation for a longer period of time. Selecting the best intersection is another main feature of CRUV. These aforementioned techniques create the problem of routing overhead as the vehicles are not allowed to share the road density with

TABLE 4. *Continued* Comparison of optimization criteria and technique of the routing protocols for UAV-aided VANETS.

Protocol	Location prediction technique	Segment scoring	Road segment division	Security concern	Vehicle's direction consideration	Broadcast mitigation technique	End-to-end delay consideration	Protocol's complexity	Communication reliability	Simulator
DCUVP	x	x	x	x	x	x	x	High	Medium	-
CRUV	x	✓	x	x	x	x	✓	Medium	Medium	NS-2
GACP	x	x	x	x	x	x	✓	Medium	Medium	Matlab
ZRPUV	✓	✓	✓	x	✓	✓	x	Medium	High	NS-2
UVAR	x	✓	✓	x	x	x	✓	Medium	High	NS-2
EUVAR	x	✓	✓	x	x	✓	x	Medium	High	NS-2
VDNET	✓	x	x	x	x	x	✓	Medium	High	-
DURP	x	x	x	x	x	x	✓	Medium	Medium	-
DBVP	x	x	x	x	✓	x	✓	High	High	NS-2
LEUV	✓	x	x	x	x	✓	✓	Medium	High	NS-2
MPUVP	x	x	x	x	x	x	✓	Medium	Low	-
ASJRL	x	x	x	✓	x	x	✓	High	High	-
TURP	x	x	x	✓	x	x	✓	Low	Medium	NS-2
UVPN	x	x	x	✓	x	x	x	Medium	Medium	-
USCF	x	x	x	x	x	x	✓	Medium	Low	NS-2
VRUA	x	x	x	x	x	x	✓	High	High	Custom-Python simulator
SURP	x	x	✓	x	✓	x	✓	High	Low	Matlab
RPUBN	x	✓	✓	x	x	✓	x	Low	High	NS-2

Note: "*x*" means the absence of the technique and "✓" means the presence of the technique.

other vehicles. The performance evaluation results show that the CRUV achieves the prime objective successfully.

ZRPUV [59] adopts a functional technique to mitigate the overhead problem of the network. The performance evaluation of ZRPUV does not show the impact of the number of UAVs. As the main goal of using UAV is to overcome the problems of shortage of RSUs and to establish communication beyond obstacles, the simulation environment should express the performance of the routing protocol in such a scenario.

UVAR [60] utilizes UAV for road condition data collection and then shares the information with other ground vehicles as well as with other aerial nodes. Though the performance evaluation results do not show the routing overhead of the protocol, this protocol should generate the least number of overhead packets. Also, the presence of the obstacles is not taken into performance consideration.

EUVAR [61] is the upgraded version of UVAR, which exploits UAVs better than any other routing protocols. The communication paradigm in this protocol reduces the overhead and the number of hops, and increases throughput. EUVAR inherits quality characteristics from UVAR and divides the whole routing criteria into two different segments.

VDNET [62] is specially designed for sparse networks, where some of the vehicles have onboard UAV. However, being designed for the sparse network, the network area is assumed only 1000 $m \times$ 1000 m. The communication range for both UAVs and ground vehicles are assumed 30 m. Both of the assumptions do not match the capability of the wireless system in the real world. However, this protocol will result in the best EED in the case of DTN.

DURP [63] uses UAVs as the data dissemination point. The channel characterization and throughput calculation are taken into serious consideration and evaluated thoroughly

whereas other performance metrics of the routing paradigms are missing.

DBVP [64] introduces the data routing mechanism in sparse network conditions in the highway scenario. The performance of DBVP is evaluated for different angles by varying the density of vehicles and drones.

LEUV [65] introduces a broadcast mitigation technique to reduce the power consumption of UAVs. However, the performance evaluation results do not show how much power is being conserved by the technique. The protocol was compared with up-to-date protocols in UAV-assisted VANETs in order to show the strength of the protocol.

MPUVP [66] illustrates the total network formation and the usage of scout UAVs while taking the UAV power consumption into consideration.

ASJRL [67] shows the impact of the jammer in the routing technique and UAV's utility. In ASJRL, data needs to pass through the UAV before reaching the RSU which introduces extra delay. While the performance evaluation technique successfully shows the UAV's impact on the BER rate, it misses the adverse effect of the extra filtration. Some results about the delay analysis would have made the scheme more acceptable.

TURP [68] as a security routing protocol shows the detection and avoidance of malicious nodes while routing data packets towards the destination. This literature adopts techniques for avoiding overhead. The detection and routing performance is shown elaborately for different conditions such as highway and city environment.

UVPN [69] considers the variable speed of the ground vehicles for clustering techniques. The effect of the speed on the routing paradigm in the presence of a non-cooperative node is analyzed.

USCF [70] adopts the technique to forward data only to the same direction vehicle by analyzing the neighbor vehicle's moving direction. This technique should bring a positive impact on data duplication in DTN networks. As UAV is used for the SCF mechanism, some more performance evaluation parameters such as hop count in the presence or absence of the UAV should have been considered.

VRUA [71] proposes a special waypoint mobility model for the VANET scenario. The performance evaluation results show that the special mobility model returns better results than the random waypoint models.

SURP [73] protocol compares its delay performance with other state-of-the-art routing protocols. This protocol ensures a durable UAV operation.

RPUBN [58] takes UAV's energy into design consideration. However, the amount of generated overhead is higher in comparison to other protocols.

B. DISCUSSION ON OPTIMIZATION CRITERIA AND TECHNIQUES

The "localization-aware simulation" heading states whether any real-world piece of map is taken into consideration for the simulation or not. One way to simulate the VANET scenario is to use the grid system without a practical traffic scenario. In such a simulation, the outcome might be better, but not for real-life application. As a result, the compatibility will always be questioned. From the above discussion, we can conclude that DCUVP, ZRPUV, TURP, and RPUBN were tested and verified for the real-life implementation.

Road segment division and road segment scoring are relatively dependent on each other. It is found that some protocols divide the road into segments but do not take segment scoring for routing decisions. Here, two different optimization criteria are discussed. The performance of a VANET protocol heavily dependent on the consideration of the road segment. Considering multiple road segments makes the protocol more realistic because the road segment intersection has its own merits and demerits. Giving special consideration to the road segment and intersection makes the protocol more reliable and suitable in real-life applications. However, a protocol developed for highway scenarios can avoid the consideration of multiple road segments, but the protocols developed for urban scenarios should consider multiple road segments and include road intersection in protocol development as well as in simulation. CRUV, ZRPUV, UVAR, EUVAR, SURP, and RPUBN consider multiple road segments. Segment scoring depends on the protocol design. The performance might or might not be improved after using the segment scoring technique. From this discussion, it can be concluded that the aforementioned protocols are more suitable for the urban road condition.

The consideration and optimization of UAV altitude are related to the ground coverage of the UAV. The exact number of UAVs can be calculated and optimized based on the altitude of the UAV and the number of ground nodes available at a specific time. The energy consumption of UAV is also dependent on the optimality of UAV altitude. GACP, DBVP, MPUVP, and USCF take UAV's altitude into consideration.

UAV's energy consumption is one of the crucial factors in UAV-aided VANETs. The route built with the help of UAVs is usually more reliable till the UAV service collapses for any reason such as UAV's energy depletion. Route selection considering UAV's energy in mind will make the routing protocol more robust, and both packet drop ratio and path failure ratio will decrease dramatically. From Table 3, it can be seen that GACP, DURP, LEUV, MPUVP, TURP, SURP, and RPUBN take the measurement of UAV's energy, which should leave a good impact on the link disconnection and path failure.

The availability of UAV depends on UAV's path planning and UAV's number. SCF role can be drastically improved with an optimized UAV path planning. Among all the discussed routing protocols, VDNet uses customized SCF path planning which will result in the shortest UAV flight and optimization of energy consumption. It is observed that UAV spends more energy on mechanical purposes such as flying rather than data transmission.

UAV has a special capability of giving DTN support. Including DTN support would make any routing protocol

for UAV-aided VANETs more reliable. SCF role-playing is related to the DTN support of the network.

For a cost-effective multiple UAV-aided VANET, the required number of UAVs should be calculated. It is predictable that a larger number of UAV will increase the coverage. With the increasing coverage, the number of redundant UAVs is also increased. Depending on the need and applications, the number of UAVs should be minimized. From table IV, it is observed that GACP, DURP, DBVP, LEUV, UVPN, VRUA, and SURP protocols try to utilize the optimal number UAVs.

For VANET routing protocols, considering vehicles' direction is an important factor. In UAV-aided VANETs, the direction for ground vehicles and UAVs are equally important. As far as the concern goes for UAV's direction, it is more complicated as a UAV can move freely in 3D coordinates. Without considering the direction, a routing protocol will not perform well in real-life applications. The direction consideration for UAV is vastly related with the mobility model that the UAV is working on. If the ground vehicles are aware of the mobility model of the UAV, the vehicles will be able to predict the next position of the UAV easily. Only ZRPUV, DBVP, and SURP protocols consider the vehicle direction in their design paradigm.

Broadcast mitigation and end-to-end delay are also important performance metrics. Table 4 indicates that ZRPUV, EUVAR, LEUV, and RPUBN protocols aim to optimize the broadcast problem whereas most of the protocols try to optimize end-to-end delay.

DTN-supported protocols must be concerned about UAV's energy consumption. It can be observed from Table 4 that most of the protocols are availing DTN support, but only a few take UAV energy optimization into consideration.

The header "protocol's complexity" is evaluated solely based on the author's opinion and the decision is taken on the basis of the solution reported in the literature. For comparing the protocol's complexity, the run-time assumption, the optimization criteria, and the covered area are taken into consideration. For evaluating the communication reliability, the recovery policy, packet drop ratio, and operation principles of the protocols have been taken into consideration

V. OPEN RESEARCH ISSUES AND CHALLENGES

In this section, various research challenges and issues are addressed. As an airborne network, UAVs are hindered by similar challenges to FANETs, in addition to several unique challenges due to their physical size and the policies imposed by the different governments. In comparison, ground vehicles are highly mobile nodes. Although the structure of most roads is static, every phase of vehicular networking is challenging because of the variable speed involved. In UAV-aided VANET architectures, UAVs are used to assist the vehicular network to increase the network's scalability, stability, durability, reliability, and securities. However, given that a heterogeneous network paradigm is utilized, UAV-aided VANET suffers from almost all the problems of UAV networks and VANETs.

The challenges and research issues outlined in this report will assist researchers in the design and implementation of more efficient routing protocols for the UAV-aided VANET architecture.

A. SECURITY AND PRIVACY
This is one of the major concerns in any network design. In addition to all the data security issues, UAV-aided VANET is also hindered by physical damage issues. There is a high probability of damaging or stealing the UAVs from the deployment area. In terms of data security, several secured protocols have already been published for VANETS and UAV networks such as [42], [74]–[76]. With the rapid deployment of UAV-aided VANET, new security concerns will arise that will be different from that of the niche networking platforms but will exhibit inherited traits.

B. CONNECTIVITY STABILITY
Establishing and maintaining connectivity between UAV and ground vehicles is one of the conditions required for routing in a UAV-aided VANET architecture. Given the dynamic environment, the network lifetime of the UAV-aided VANET is significantly low. An effective routing scheme will attempt to maintain a link lifetime for as long as possible. Moreover, monitoring of the link health can assist in re-routing data using previously established links, which may significantly reduce the required time. Link failure in communication initiates new discovery processes that increase packet delivery delay, data loss, network congestion with extra control packets.

C. ENERGY CONSUMPTIONS
Power requirement is one of the crucial factors in UAV assisted networking services. UAVs should have long lifetimes to effectively support rescue vehicles in remote or disaster-affected areas. In [75], the authors concluded that to reduce power consumption, UAVs should store data and calculations should be kept for subsequent analysis. In contrast, vehicle data should be transmitted in an aggregated way to reduce transceiver usage. Aerial vehicles can also be divided into zones to reduce communication overlapping and duplicate data transmission.

D. PRIORITY ROUTING
Due to uncertain data delivery issues, protocols should maintain the option of priority routing for special cases. However, maintaining prioritized packet delivery options with other normal packet delivery at an optimal level raises another issue.

E. FAULT TOLERANCE
The UAV-aided VANET has an architecture that is inherently prone to disconnections. Owing to high mobility, a stable connection is difficult to maintain between both the root architectures; namely, VANET and UAV networks. A good routing algorithm should consider these unique characteristics and

should include a fault tolerance mechanism as part of the design. Fault tolerance mechanisms have a direct impact on the packet delivery ratio (PDR) and the end to end delivery delay. Opportunistic delivery is a common fault tolerance technique implemented in the architecture.

F. HIGH MOBILITY AND DYNAMIC TOPOLOGY SCENARIO

Some drones cruise up to 45 m/s [50], whereas the speed of vehicles varies significantly and can approach 200 km/h [77]. Ground vehicles encounter traffic congestion issues however, drones have relatively free space for roaming. Due to the highly mobile situation, topological changes frequently occur. The transmission of data among V2V networks or V2U networks becomes difficult due to the frequent topological change.

G. DISCONNECTIVITY LOCALIZATION

To maintain ad hoc connectivity, UAVs should be placed in optimal locations where the vehicles experience frequent disconnections or are likely to encounter disconnections in the near future. In these cases, the vehicles can use the aerial vehicle as relay nodes. However, in an urban area, even though a road may be identified as loosely connected, the situation might change before the arrival of the UVA. Therefore, the future localization of disconnected areas is an important issue in UAV-aided VANET architecture.

H. SCALABILITY

Vehicular network connectivity is highly dependent on the number of vehicles on the road. The need for the assistance of UAVs increases when the number of vehicles decreases. Moreover, if the road becomes sparse or if there is a limited number or no RSUs on the segment of interest, the need for UAVs also increases. However, as the number of vehicles decreases, the number of transmission requests will also decrease. Sometimes the vehicles require continuous data transmission. In such cases, the connectivity should be maintained all the time. Therefore, depending on the requirements and other important factors, the network should adaptively be able to scale up or down.

I. LOW LATENCY

In UAV-aided VANET scenarios, the transmission window is narrow and in the case of ITS, the service size of the requested data for transmission can be very high. As a result, a low latency network is required for a UAV-aided VANET networking scheme.

J. AUTONOMOUS OPERATION OF UAVs FOR VANET

Co-ordination among UAVs is necessary to deploy UAV-aided VANET services on a large scale. Transmission range overlapping, an excessive number of UAV usage, non-discovered sparse segment, latency in convergence time, and many other challenges are encountered in the absence of coordination among the UAVs. The UAVs should have the ability to execute orders from other nodes depending on role play

and they should also be able to implement emergency decisions based on their capacity. Further enhancement should be undertaken to facilitate enhanced team-play among UAVs.

K. SPECIALIZED MOBILITY MODEL

Most UAV-aided VANET architectures are built based on a random mobility model. With the increasing number of UAV aided services, this architecture will eventually be unable to exploit these mobility models. Coordination and cooperation will be a major issue for different kinds of UAV-based services in the future.

L. QoS AND PERFORMANCE ANALYSIS

Depending on the application, the QoS requirements change and the routing protocol should respond accordingly to achieve the ultimate goal. Throughput maximization, overhead optimization, delay constraint routing, energy-efficient routing, secured routing, UAV number optimization, dependency on static infrastructure, DTN supported routing, etc., are all separate research issues in this type of network. Some of the QoS are complementary to each other.

VI. CONCLUSION

In this article, the routing techniques for UAV-aided VANETs have been extensively surveyed and comparatively analyzed. The following paragraphs show the key achievements of this work, the contribution of this paper to the academics and practices, and some recommendations for future works.

The key achievements of this work are as follows: Based on the study, we can see that most of the routing protocols for UAV-aided VANETs cover partial objectives rather than covering the entire routing aspects. The protocols suggested for security reasons overlook delay and energy performance. The road intersection based solutions do not consider UAV's mobility and coverage time. The probability of incoming vehicles is considered in many protocols, but the arrival probability of UAV is neglected. Multi-UAV deployment is shown in some research works in which two layers of networking is assumed to design an efficient routing protocol. UAV's energy is one of the bottleneck of the whole architecture. All the protocols should consider the amount of residual energy and the lifetime of the UAV in order to make a practical solution whereas most of the protocols overlook this issue. Most of the protocols utilize SCF capability which adds great benefits to DTN facility, but energy consumption for SCF mechanism are absent in the protocols. In UAV-aided VANETs, UAV is characterized as a mobile RSU where considering the availability of static infrastructure is redundant and also not efficient in urban areas with less obstacles. Some protocols are introduced assuming totally infrastructure-less scenarios. Vehicle direction consideration in designing an efficient routing algorithm for VANETs is a well-utilized technique.

The contribution of this paper to the academics and practices can be summarized as follows: To the best of our knowledge, there is no survey that dedicatedly covers routing

protocols for UAV-aided VANETs. Hence, this paper will provide the reader an overall organized idea of the topic. This paper is written with a motto to facilitate the new researchers with an in-depth knowledge of the topic, by criticizing the papers intensely. For delivering background knowledge to the readers, the recent routing protocols and surveys on VANETs and UAVs have been overviewed. Then, the routing protocols have been classified according to energy, hierarchy, position, DTN, security, and cluster categories. Each routing protocol has been reviewed in detail and critically analyzed by mentioning its advantages and disadvantages. The best application areas and possible future improvements have been outlined for every protocol. The reviewed routing protocols have been qualitatively compared with each other in terms of major features, key characteristics, performance, advantages, and limitations. The qualitative comparison among the protocols have been presented in a tabular format and then rigorously discussed. The internal relation and performance dependency on the design objectives are also discussed. The important open issues and research challenges and probable solutions have also been outlined and discussed.

The following are some recommendations for future works. In Table 4, the designing objectives are given which leaves important future directions for researchers. The importance of the objective parameters and their internal dependencies is also addressed. The researchers must keep the internal dependencies of the designing objectives in mind while designing a new routing protocol or improving the existing one. In a UAV-aided VANET, UAV's energy is a crucial factor. Energy becomes a more crucial part of SCF support and thus the energy analysis should be done extensively. Besides, a good routing algorithm must consider mobility of UAV and ground vehicles. The unique mobility pattern of the UAV should be assumed or derived by the research works so that the impact of the UAV mobility model can be calculated. Location prediction techniques should be focused which will bring positive changes in the routing performances. In Section V, the less-investigated and important research issues and open challenges are discussed, which should be considered for future works. A rapidly deployable UAV-aided VANET can be an effective solution for disastrous areas as well. It should be noted that many of the discussed protocols are still in their early phase of development and thus significant improvements might be required prior to implementation for practical use. We believe that the presented information will serve as a starting point for research on routing techniques for UAV-aided VANETs, and will also generate research interest in this field.

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