

An Energy-Efficient Routing Algorithm for UAV Formation Based on Time-Aggregated Graph

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Abstract: The limited energy and high mobility of unmanned aerial vehicles (UAVs) lead to drastic topology changes in UAV formation. The existing routing protocols necessitate a large number of messages for route discovery and maintenance, greatly increasing network delay and control overhead. A energy-efficient routing method based on the discrete time-aggregated graph (TAG) theory is proposed since UAV formation is a defined time-varying network. The network is characterized using the TAG, which utilizes the prior knowledge in UAV formation. An energy-efficient routing algorithm is designed based on TAG, considering the link delay, relative mobility, and residual energy of UAVs. The routing path is determined with global network information before requesting communication. Simulation results demonstrate that the routing method can improve the end-to-end delay, packet delivery ratio, routing control overhead, and residual energy. Consequently, introducing time-varying graphs to design routing algorithms is more effective for UAV formation.

Keywords: energy-efficient route; time-aggregated graph; UAV formation

I. INTRODUCTION

Unmanned aerial vehicle (UAV) technology has been continuously innovated in the digital age. UAVs are no longer only applicable to the battlefield but are widely used in agriculture, commerce, forestry, industry, and other fields [1, 2]. It is widely emphasized as an important component in the space-air-ground integrated network [3, 4]. In addition, UAV-assisted communication is also considered an essential potential technology in 6G mobile networks [5]. UAV has many advantages such as convenient operation, diverse uses, high flexibility and lower cost. However, single UAV has limited endurance and flight range, poor survival rate, and low mission efficiency. The collaboration of multiple UAVs can perform complex tasks, which improves the working capacity and efficiency of UAVs and reduce the cost. Because the working area of UAVs is extended and the survival time and reliability are effectively enhanced by relaying communications and assigning tasks between them [6]. Therefore, multi-UAV cooperation is the future development trend.

A prominent research area in multi-UAV collaboration centers on the development of flying ad hoc network (FANET) [7]. It enables communication in a multi-hop fashion, offering high autonomy without being constrained by ground-based stations. FANET has higher node mobility, greater speed change, and more limited battery energy than traditional mobile ad hoc network (MANET) [8] and vehicle ad hoc network [9]. This poses challenges for its communication de-

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sign, particularly in routing. Consequently, designing reliable routing strategies is essential to maintain excellent communication in FANET.

FANET is a specialized type of MANET. Therefore, some scholars have applied classical dynamic routing protocols to FANET to evaluate its performance. Authors in [10] and [11] compared existing ad-hoc routing protocols such as ad-hoc on-demand distance vector (AODV), optimized link state routing (OLSR), dynamic source routing and geographic routing protocol for FANET using OPNET. They analyzed a variety of metrics such as end-to-end delay, packet loss rate, throughput, and others in various network environments. Various routing protocols exhibit different performances in FANET and no single protocol achieves the best results in all metrics.

Accordingly, scholars have optimized the traditional protocols for the characteristics of FANET. The link stability estimation-based preemptive routing protocol was proposed in [12] based on AODV to construct multiple reliable link-disjoint paths. In [13] and [14], enhancements are made to AODV in terms of forwarding indicators and routing selection, respectively. Predictive OLSR [15] enables efficient routing in very dynamic conditions. Regarding the high mobility of UAV nodes, the optimal routing is selected based on link quality and instantaneous relative speed between nodes. A 3D position-based modified OLSR routing protocol was introduced in [16] to enhance the selection of multi-point relays. [17] proposed a novel adaptive hello interval scheme, energy efficient hello (EE-Hello), based on available mission-related information aimed at decreasing energy consumption.

Moreover, software defined networking (SDN) represents a promising approach for decoupling control logic from forwarding components. SDN has been applied in UAV formation to efficiently acquire topology information and flexibly control the data plane [18–21]. An SDN-based routing algorithm was proposed for cooperative UAV networks [20]. The path lifetime and the network load are considered in selecting the routes. The algorithm balances the network load and optimizes the network performance.

Despite the improvements to the process of link probing and route discovery, the peculiarities of FANET lead to problems such as long end-to-end delay and route discovery time. The topology changes of FANET are typically time-varying. Most of the

existing routing protocols were designed based on static graph theory. Routing selections are made based solely on the resources available in the network at a specific moment, disregarding any temporal correlation. The time-varying graph introduces the property of time, which can represent resources at different moments [22]. This means that changes in the network need to be known in advance. As a special FANET, UAV formation is a predefined time-varying network [23]. The trajectories of UAVs are usually planned ahead of time to correspond with missions. Routing algorithms can be designed using time-varying graphs to fully utilize prior knowledge in UAV formation [24].

Many time-dependent flow problems can be solved by transforming them to static flow problems in the time-expanded graph (TEG) [23]. In [25], the TEG was extended to model the data acquisition and energy management for satellite networks. The multicast TEG was constructed to illustrate multicast transmission over satellite networks across time [26]. The time-aggregated graph (TAG) model [27] was designed to address the high storage overhead and computational cost drawbacks of the TEG. The storage TAG was proposed to study the maximum flow problem for delay-tolerant networks by Li Hongyan team of Xidian University [28]. They developed a flow-maximizing routing scheme to achieve a higher mission completion and resource utilization rate for satellite networks [29]. [30] proposed a polynomial-time complexity algorithm based on TEG for non-terrestrial networks. It enables the dynamic selection of optimal transmission links and cycles on a hop-by-hop basis.

Existing routing methods in UAV networks require a huge number of control packets to be sent for route discovery and maintenance. The selection of the shortest routing path is mostly based on the number of routing hops. UAV formation is a predefined time-varying network. The previous work introduced the TAG model for the route selection for UAV formation [24]. But the routing algorithm was proposed to depend only on the delay at different time slots. The endurance of the UAV formation is constrained by the limited on-board energy. Hence, a key objective of UAV formation routing and transmission protocols is to enhance the efficiency of energy usage in UAVs. An energy-efficient routing algorithm based on discrete TAG is proposed in this paper and the main contributions are summarized as follows:

- The discrete TAG model is employed to depict the resources accessible within the UAV formation. Consequently, the transmission of a significant amount of control messages is not essential for the processes of route discovery and maintenance. This reduces the energy consumption and routing control overhead.
- A link stability metric is designed according to the relative mobility and the delay between UAVs. The optimal routing path is selected according to the special metric. This enhancement leads to an increase in packet delivery ratio and a decrease in end-to-end delay.
- When selecting forwarding nodes, prioritize UAVs that have a higher amount of remaining energy. It significantly stabilizes the overall average residual energy of the entire UAV formation.

The remaining of this paper is organized as follows. Section II analyzes the topology-based routing protocols and their applicability in UAV formation. The energy-efficient routing algorithm proposal is introduced in Section III. Section IV shows the simulation results compared with AODV and AODV-EE-Hello. The paper is concluded in Section V.

II. ANALYSIS OF ROUTING PROTOCOLS

2.1 Topology-Based Routing Protocols

Due to the similarities between FANET and MANET, UAV formation mainly utilizes routing protocols from traditional MANET. This paper introduces topology-based routing protocols, which can be categorized as static, proactive, reactive, and hybrid. Their main processes and characteristics are shown in Figure 1.

Static routing protocols require manual configuration of the routing table in advance. The data will be transmitted according to the routing table. It is appropriate for networks with fix connectivity. The changed topology may result in data not successfully arriving at its intended destination.

Proactive routing protocols broadcast control messages at regular intervals to detect alterations in the network topology. This prevents the global routing table from becoming outdated. The nodes calculate the best route based on the latest stored partial link information. When a communication request is made in

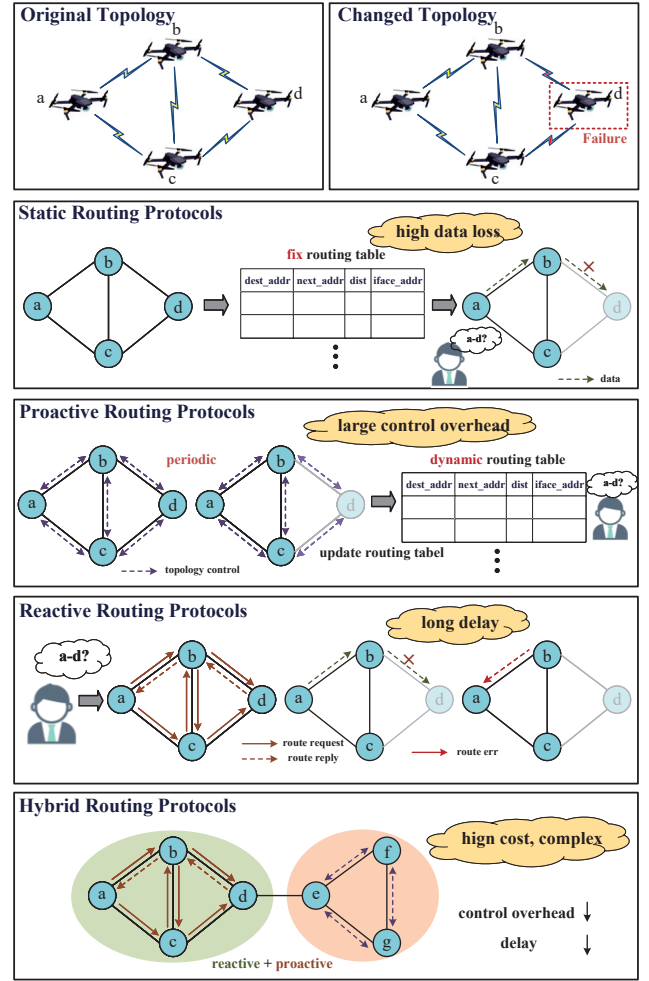


Figure 1. Topology-based routing protocols.

the network, the source node carefully checks the local routing table to identify the correct forwarding route.

Reactive routing protocols are also known as on-demand routing protocols. Route request (RREQ) messages are produced by the network exclusively when there is a requirement for data transmission to facilitate the establishment of a routing path from the source to the destination. It is not essential to maintain routing tables for every node within the network. Accordingly, they can diminish the routing control overhead in comparison to proactive routing protocols. While on-demand route discovery and maintenance cause longer delay and higher jitter.

Hybrid routing protocols integrate the advantages of both proactive and reactive routing protocols. They divide the network into two regions using separate protocols. The rules governing regional adjustments are complex and significantly impact performance. They

incur higher costs and introduce greater complexity.

2.2 Applicability Analysis in UAV Formation

The UAV formation is a special MANET. The high mobility and limited energy of UAV lead to frequent topology changes. In the absence of direct end-to-end communication pathways, the interaction among UAVs primarily relies on a multi-hop communication approach. These characteristics make traditional routing protocols exist many drawbacks in the network.

Static routing protocols are suitable for networks with fixed topologies. Despite the stability of the UAV formation pattern, the finite energy capacity of the UAVs will result in alterations to the topology. The UAV formation needs to vary its queues to perform multiple tasks. The changed topology can cause an incorrect routing table, leading to substantial data loss.

In proactive routing protocols, every UAV shares the most recent routing information with other UAVs in the formation, regardless of the need for communication. All UAVs exchange routing information, which is maintained in individual routing tables for each UAV. And these tables are updated periodically. High reliability and low delay are advantages of proactive routing protocols. In UAV formation, frequent topology changes lead to more often updates and sharing, resulting in increased control overhead. And it shows very poor scalability as the network scale increases.

Compared with the proactive routing protocols, the reactive routing protocols do not need to periodically broadcast control messages. The source-destination routing path is discovered and maintained when the UAV formation needs to communicate. In the absence of an available correct path, the protocols will initiate route discovery and route repair processes, which are exclusively designed for single-path scenarios. UAVs are not obliged to maintain routing information to all UAVs in the network. The reactive routing protocols have less overhead and higher bandwidth utilization.

The AODV routing protocol is a typical on-demand routing protocol that establishes a single transmission route to reach the destination node. It can provide rapid adaptation to dynamic link conditions. The main processes are route discovery and route maintenance. The effectiveness of the designed algorithm is verified in this paper by comparing with AODV.

When a UAV in the network needs to reach a new

destination UAV, it enters the route discovery process. The source UAV will broadcast RREQ messages to find a route to the destination. The RREQ messages reach the destination or an intermediate UAV with a valid route entry to the destination, indicating that a route has been identified. A route reply (RREP) message will be sent to the source node as in the point-to-point mode and this route will become valid. A UAV may receive multiple RREP messages from neighboring UAVs. It will only forward the first RREP message it receives unless a subsequent RREP exists with a larger sequence number or a shorter routing hop count.

Each UAV monitors the link status of the active routes to reach the next hop by sending HELLO messages. When a link break is detected in active routes, route err messages will be used to notify other nodes. These messages indicate that the destination nodes have become unreachable due to link disruption. The local route repair mechanism will be activated in the UAV formation. The upstream UAVs initially store information regarding the source node upon detecting a disruption in the connection. Subsequently, they send RREQ messages to the destination node to rebuild the route. If the route reconstruction fails, the source UAV will be notified to rebroadcast the RREQ messages. Above is the process of route maintenance in AODV.

The AODV route protocol needs to utilize RREQ, RREP messages to establish routes, which can lead to long delay. Frequently disrupted links in UAV formation result in high overhead during the routing maintenance process. The prior knowledge within the network is not effectively leveraged, as route selection is based solely on the number of hops at a given time rather than identifying the optimal path. Time-varying graph can characterize the resources in the UAV formation at different moments. It is utilized to design routing algorithms that can improve all aspects of performance comprehensively.

III. ENERGY-EFFICIENT ROUTING ALGORITHM BASED ON DISCRETE TAG

3.1 Discrete TAG for UAV Formation

The topology, nodes and links, and other available resources of a time-varying network change over time. UAV formations with time-varying resources fall into this category of networks. The time-varying graph in-

roduces a temporal attribute that can effectively leverage time-varying resources. The resources of the UAV formation are represented as a corresponding time-varying graph. The optimal routing path is then determined by designing an appropriate routing algorithm.

Figure 2 presents a simple example illustrating the discrete TAG. The resources in the UAV formation at each instant in time are represented as graphs. The UAVs and communication links are abstracted as nodes and edges, respectively. The link weight can be delay or other values of interest. The TAG [27] aggregates the discrete topologies onto a graph, and uses a series to represent the time-varying link weight. The more time slots are divided in a fixed time, the more accurate the network topology described by the TAG. In contrast to TEG, the TAG does not need to duplicate the nodes and edges of the network. Thus this graph model greatly reduces the storage overhead.

The shortest path algorithm in time-varying graphs calculates the minimum cost routes in time-varying networks. Link weights may be configured in accordance with the specific attributes of the network.

The variability in the direction and speed among different UAVs leads to poor stability of the communication links in the UAV formation. UAVs have limited energy and face challenges with recharging during missions. They continuously consume energy for flight and data transmission, which can reduce network connectivity. This high energy consumption may overload UAVs, potentially causing damage. In order to establish stable transmission links during routing selection, a link stability metric λ is designed in this paper. It is the link weight in TAG and defined as

$$\lambda = \alpha\sigma_{ij} + \beta d_{ij}, e_j \geq e_{th}, \quad (1)$$

where σ_{ij} is the relative mobility metric and d_{ij} is the delay of node i and j . e_j denotes the initial energy of neighbor node j and e_{th} denotes the energy threshold. α, β are weight coefficients, which satisfy $\alpha + \beta = 1$. Here, α and β are both set to 0.5 and the values can be adjusted according to different situations to adapt varying network requirements.

From Eq. (1), the smaller the relative mobility and the delay between UAVs, the more stable the corresponding link will be. This means that the best routing path is the link with the lowest sum of weights λ . The residual energy of the next-hop UAV should exceed a

predefined threshold to reduce the occurrence of path failure due to node disappearance.

Since the UAV formation is the predefined network, it is possible to obtain the link delay d_{ij} , the 2D velocity of each UAV in every time slot. The relative mobility metric σ_{ij} between the current UAV and its neighboring UAV can be calculated with respect to their velocities. The value largely determines the stability of the link between UAVs. Nodes with smaller σ_{ij} produce shorter relative movement distance. The likelihood of data loss during the transmission process is reduced.

The relative moving speed of node i and node j can be calculated by

$$v_{ij} = \sqrt{(v_{ix} - v_{jx})^2 + (v_{iy} - v_{jy})^2}, \quad (2)$$

where v_{ix}, v_{jx} and v_{iy}, v_{jy} denote the velocity components along the horizontal and vertical directions.

The relative mobility metric σ_{ij} can be expressed by

$$\sigma_{ij} = \frac{v_{ij}}{v_{ij\max}}, \quad (3)$$

where $v_{ij\max} = |v_i| + |v_j|$. $|v_i|$ and $|v_j|$ are the absolute values of the velocity of the nodes.

3.2 Energy-Efficient Routing Algorithm

The shortest path algorithm in TAG is different from that in static graph due to the introduction of temporal property. Because the paths do not always display greedy attribute or optimal substructure. And they are usually related to the start time at the source node.

In Figure 3a, the link weight is delay. The shortest path ($a-c-d-e$) takes 6 time units from node a to node b for the start time $t = 1$. But the path from a to d takes 4 time units following the above path and is not optimal. The path $a-b-d$ only takes 2 units of time. As a result, paths in TAG do not exhibit the optimal prefix property. This situation is analogous when link weights represent other types of costs.

Assuming the nodes do not follow the first in first out (FIFO) property, the greedy strategy cannot be used to find the optimal path. It means that the data can wait at nodes in the UAV formation. In Figure 3a, the data is sent at node a in the first time slot and passes through b to reach d . If the FIFO property is not followed, the

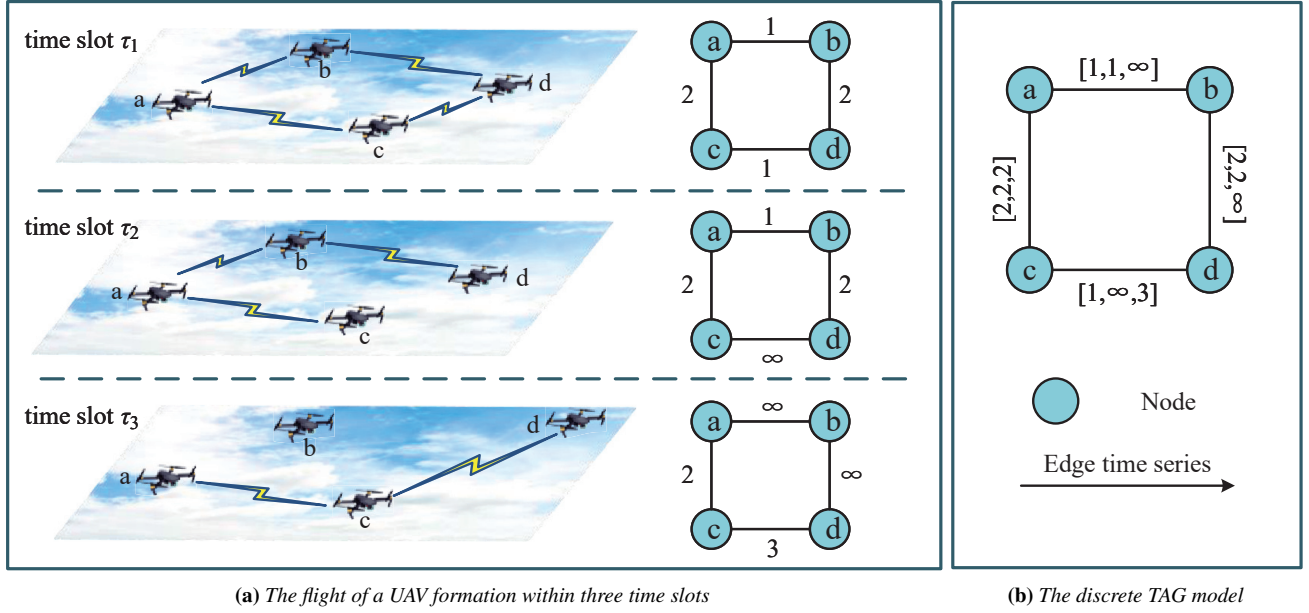
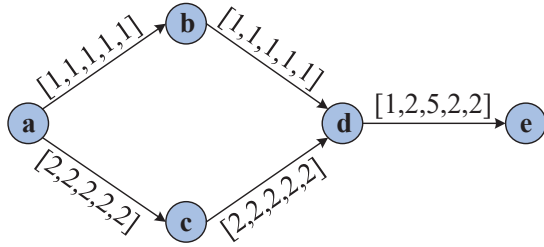
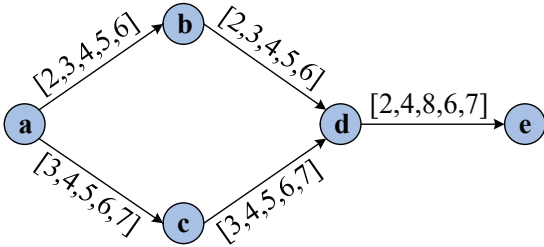


Figure 2. The discrete TAG model of a simple UAV formation.

data will wait for one time slot at d to be forwarded to e . The path takes 5 units of time, which is shorter than the path $a - c - d - e$. The optimal path can be found in non-FIFO network.



(a) The original TAG model.



(b) The transformed TAG after ATST.

Figure 3. A example of ATST in TAG.

To simplify the computation of shortest paths in discrete TAG, the delay series of the link is converted using arrival time series transformation (ATST), as shown in Figure 3. The optimal substructure is valid

in the transformed TAG. The time series on the link between node a and node b in the network after ATST indicate the arrival time $T_{ab}(t)$ which is the sum of departure time t and the delay $\sigma_{ab}(t)$ ($T_{ab}(t) = t + \sigma_{ab}(t)$). ATST is the basis of the shortest path algorithm. The arrival time series is used in energy-efficient routing algorithm.

As mentioned in Section 3.1, the stability of the link is affected severely by the relative mobility between UAVs and the residual energy in UAV formation. Thus a special metric is designed to solve the stable routing path. It is used to compute the series of weights for TAG. As shown in Algorithm 1, an energy-efficient routing algorithm based on TAG is proposed to maximize the link stability. The key points of the algorithm can be outlined as follows. First, the discrete TAG is constructed by the moving trajectory and available resources of the UAV formation. The link stability metrics in different time slots are calculated using Eq.(1). The optimal routing path is computed by the delay series and the link stability series. Second, the link delay series is transformed into an arrival time series utilizing the ATST rule. The previous hop of all nodes and the cost to other nodes are initialized in TAG. Next, two collections are established to contain adjacent nodes and nodes that have not yet been traversed. The residual energy of the adjacent nodes is

greater than the threshold. The node that has the minimum link stability metric is selected after the arrival time of the current node. And the cost, the arrival time and the parent node of the next node are updated. The algorithm ends when all nodes have been traversed.

Algorithm 1. *Energy-efficient routing algorithm.*

Input: the trajectory of the UAV formation in a given time horizon, the source node s , the destination node d , the start time t_{start} , the initial energy e_i of each node and the residual energy threshold e_{th}

Output: the energy-efficient routing path from s to d at time t_{start}

- 1: according to the formation moving trajectory, compute the discrete TAG $G = \{V, E\}$ with a set of nodes V , a set of edges E and each edge $e \in E$ has a corresponding link delay series and stability metric series Λ . The link stability metric λ is given in Eq.(1)
- 2: the link delay series is converted into the arrival time series T by ATST
- 3: initialize variables: $t_s = t_{start}$; $c_{ss} = 0$; $\forall m \neq n, c_{mn} = \infty$; $p_m = -1$; $Q = \{s\}$; $P = \emptyset$; // t_s denotes the arrival time of node s ; c_{mn} is the cost at the node n from the node m and p_n is its previous hop, while -1 means no previous hop
- 4: **if** $Q \neq \emptyset$ **then**
- 5: extract the head node u from Q and insert its neighbor nodes with $e \geq e_{th}$ into P
- 6: **if** $P \neq \emptyset$ **then**
- 7: extract the head node v from P , and calculate $c_{uvmin} = \min \{\Lambda_{uv}(t), t > t_u\}$, $c'_{sv} = c_{su} + c_{uvmin}$
- 8: **if** $c'_{sv} < c_{sv}$ **then**
- 9: update the minimum cost $c_{sv} = c'_{sv}$, the arrival time t_v according to the series and the parent node of v $p_v = u$
- 10: **if** v was not traversed, insert v in Q
- 11: **end if**
- 12: **else**
- 13: return step 4
- 14: **end if**
- 15: **end if**

Algorithm 1 computes the optimal routing path according to the global network information before generating communication request. The algorithm assumes finite time windows. The entire routing method in this paper does not need to send a large number

of control messages for route discovery and maintenance, thereby contributing to a reduction in energy consumption. UAVs with residual energy exceeding a specified threshold are selected to ensure an equitable distribution of energy within the UAV formation. This routing algorithm substantially improves the longevity of the network.

IV. PERFORMANCE EVALUATION

4.1 Evaluating Parameters

The following parameters are selected to evaluate the performance of the routing protocols in UAV formation [12].

- **Average End-to-End Delay:** The average time taken for data packets to reach the destination UAV from the source UAV.

$$EED_{avg} = \frac{\sum_{i=1}^n (t_r(i) - t_s(i))}{n}, \quad (4)$$

where $t_r(i)$ is the time of receiving the data packet at the destination and $t_s(i)$ is the time of sending the data packet at the source. n denotes the number of data packets successfully received.

- **Packet Delivery Ratio:** The ratio of packets received by the destination UAV to the packets sent by the source UAV.

$$PDR = \frac{P_r}{P_s}, \quad (5)$$

where P_r denotes the number of packets actually received at the destination and P_s is the number of packets theoretically sent at the source.

- **Routing Control Overhead:** The ratio of control packets to all packets sent in the network. Control packets encompass packets utilized for route discovery and route maintenance.

$$RCO = \frac{P_c}{P_s}, \quad (6)$$

where P_c is the numbers of control packets and P_s denotes the number of sent packets by the source UAV.

- **Average Residual Energy:** Average residual energy across all UAVs in the network [31].

$$RE_{avg} = \frac{\sum_{i=1}^N (E_{ri})}{N}, \quad (7)$$

where E_{ri} denotes the residual energy of active UAV i and N is the number of UAVs in formation.

4.2 Simulation Setup

The performance of the proposed routing method, including metrics such as end-to-end delay, packet delivery ratio, route control overhead, and average residual energy, is evaluated in comparison to typical AODV and AODV-EE-Hello [17]. Multiple simulations were carried out for every number and speed of UAVs. The impact of node density and speed are analyzed by varying the number of UAVs from 20 to 100 and their speed from 10 to 90 m/s. Rest of the simulation parameters are described in Table 1 [12].

10 different random seeds are set up in the simulation to test the performance of three routing methods. This can guarantee the randomness of simulations and the reliability of results. The final outcome is derived from the average of 20 simulation runs.

Table 1. *Simulation parameters.*

Parameters	Value
Simulator	NS-3
Simulation Area	1000 m × 1000 m
Mobility Model	Random Way Point
Number of UAVs	100
Speed	30 m/s
Simulation time	200 s
MAC Protocol	802.11g
Bandwidth	2 Mbps
Initial Energy	60 J
Data Packet Size	512 bytes
Packet Rate	4 packets/s
Traffic Type	CBR
Transmitted Distance	250 m
Maximum Queue	5
Bandwidth	2 Mbps

4.3 Simulation Results

This subsection analyzes the simulation results of the proposed routing protocol, AODV and AODV-EE-Hello. The analysis considers different numbers and

speeds of UAVs. The results demonstrate that the proposed routing method exhibits superior performance.

In Figure 4, with the increasing number of UAVs, the average end-to-end delay decreases. This is attributed to the fixed simulation area, where the growing UAV count leads to a reduction in the end-to-end distance. As illustrated in Figure 5, increasing UAV speed results in more rapid positional changes, which consequently leads to a corresponding rise in delay. The average end-to-end delay of the energy-efficient routing method is lower than that of both the AODV and AODV-EE-Hello. The difference becomes more pronounced with varying speeds. AODV and AODV-EE-Hello require the dissemination of large messages to establish a source-destination routing path after requesting communication, leading to considerable time consumption. Yet, the proposed method based on TAG achieves the routing path before initiating communication requests. It leverages prior knowledge of the network. So this method can significantly reduce delay.

Increasing nodes in UAV formation enhances network connectivity in the designated flight area. More available relay nodes can be selected between the source and destination UAVs. Thus the packet delivery ratio improves with increasing number of UAVs in Figure 6. Increasing speeds contribute to more drastic topological changes, dropping the packet delivery ratio, as seen in Figure 7. The energy-efficient routing protocol is significantly better than AODV and AODV-EE-Hello for this metric. It fully utilizes the resources of UAV formation and selects the optimal routing path based on global network information before generating communication requirements. Furthermore, the routing method considers the relative mobility between UAVs when selecting the paths. Thus the routing paths are more stable and less broken. AODV and AODV-EE-Hello require sending RREQ messages to establish routing. Due to frequent topology changes, the selected routing paths are prone to failure.

In Figure 8 and 9, the control overhead of AODV and AODV-EE-Hello increases significantly with the rise in node density and speed. It increases marginally for the proposed routing protocol. The overhead of the former is larger than that of the latter. With the increasing number of UAVs, AODV and AODV-EE-Hello need to send more RREQ and RREP messages for route discovery. Higher speeds result in more frequent route failures, requiring additional control pack-

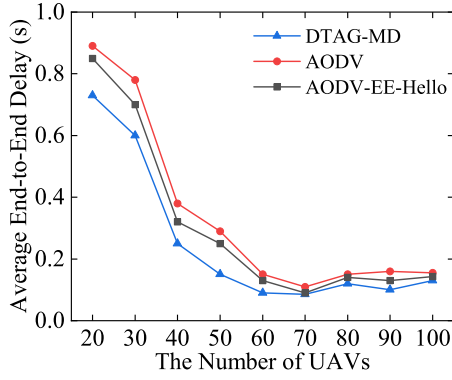


Figure 4. Average end-to-end delay vs number.

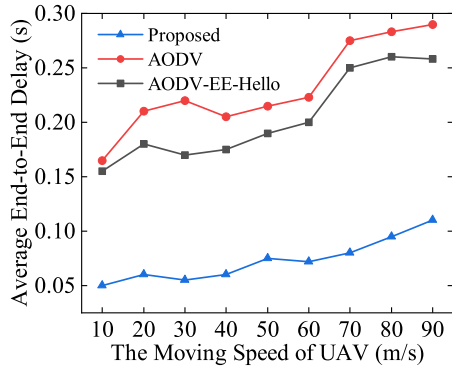


Figure 5. Average end-to-end delay vs speed.

ets for route maintenance. The proposed method sends control messages to inform the upstream UAVs of the link state only when the route fails. And the path is more stable due to the consideration of residual energy and relative mobility. Consequently, the routing control overhead exhibits a gradual increase and is considerably less than AODV and AODV-EE-Hello.

The influence of the quantity and speed of UAVs on the average residual energy of the UAV formation is depicted in Figure 10 and 11. The average residual energy decreases gradually with the increase in both the quantity and speed of UAVs. The average residual energy of the proposed protocol is obviously higher than that of AODV and AODV-EE-Hello. UAVs using AODV and AODV-EE-Hello not only consume energy to send data packets and maintain flight status. They also require a huge amount of energy to send and process routing control messages to ensure the freshness of routing paths. Even if AODV-EE-Hello implements an adaptive hello interval scheme, the proposed routing method is better than it. UAVs using the energy-efficient routing protocol based on the discrete TAG

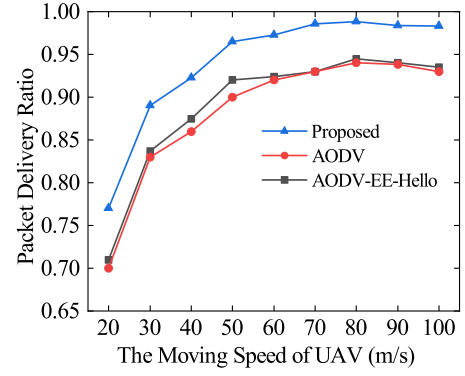


Figure 6. Packet delivery ratio vs number.

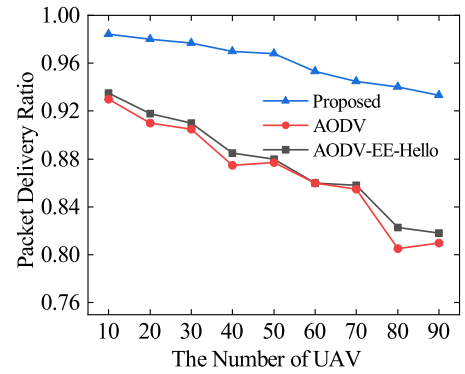


Figure 7. Packet delivery ratio vs speed.

allocate the majority of their energy towards sending and processing data packets. Moreover, the proposed routing protocol prioritizes UAVs with initial residual energy exceeding a predefined threshold when calculating routes. This strategy greatly balances the average residual energy of the entire UAV formation.

V. CONCLUSION

In this paper, an energy-efficient routing algorithm was proposed based on TAG for UAV formation. The TAG was introduced to characterize the resource at different time slots because UAV formation is a pre-defined time-varying network. The relative mobility and delay between UAVs were jointly considered to design the link stability metric as the weight of TAG. The proposed routing method select the optimal path according to the weight series of TAG and the residual energy of UAVs. It efficiently improve the end-to-end delay, packet delivery ratio, routing control overhead and residual energy compared with AODV and AODV-EE-Hello.

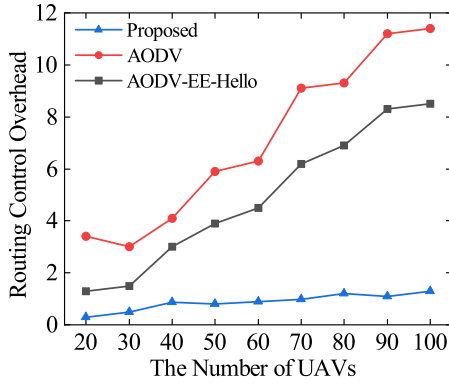


Figure 8. Routing control overhead vs number.

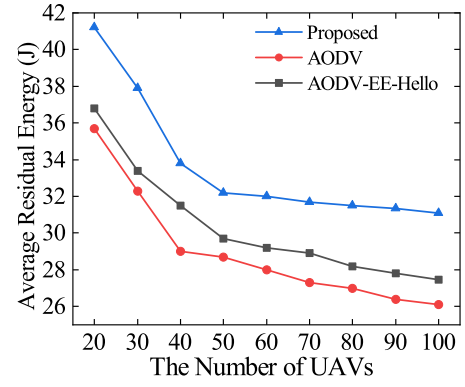


Figure 10. Average residual energy vs number.

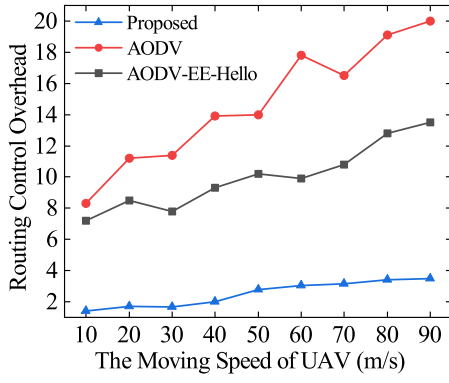


Figure 9. Routing control overhead vs speed.

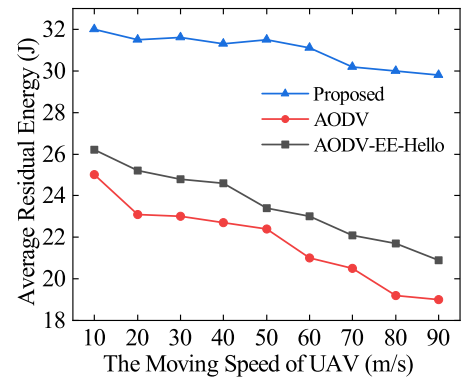


Figure 11. Average residual energy vs speed.

The more appropriate time-varying graphs will be designed with the characteristics of UAV in further work. More practical routing protocols are created by integrating dynamic routing algorithms with time-varying graph-based routing algorithms. It is essential to explore more precise network models for stochastic time-varying networks.

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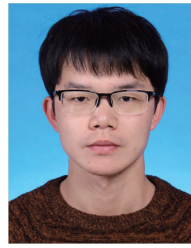


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