A Hierarchical Routing Protocol Based on AODV for Unmanned Aerial Vehicle Swarm Network

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***Abstract*—With the development of unmanned aerial vehicle (UAV), UAV swarm network is becoming more and more popular for broad application. Compared with a single UAV to perform tasks, the UAV swarm network is the future significant trend. However, the expansion of the network scale will bring broadcast storms to the UAV swarm Ad Hoc network, resulting in the drop of packet delivery ratio. Therefore, this paper proposed a hierarchical routing protocol weighted-based clustering AODV (WBC-AODV) based on the clustering structure. Under this routing protocol, the cluster head node can effectively manage the routing establishment of member nodes, which can reduce the repeated forwarding of control data packets in the process of flood routing, and reduce the probability of data packet collision. The experimental results show that the proposed method can improve the packet delivery ratio of the network, but at the same time it will increase the average end-to-end delay of the network.**

Keywords—UAV, AODV, weighted-based clustering algorithm, hierarchical structure

I. INTRODUCTION

With the utilization of unmanned aerial vehicle (UAV) in military and civil fields, it has become possible for self-organizing UAVs to perform tasks in groups. However, large-scale UAV swarms can generate excessive duplicate information in the network, which can cause broadcast storms problem (BSP) and affect the performance of network [1]. The key to solving BSP is to reduce broadcast information. Common solutions are classified into the following types: counter-based, probability-based, location-based, and clustering-based [2]. Among them, since the network can be effectively managed under the clustering structure, clustering is also the most commonly used solution [3]. In addition, the problem of routing needs to be solved. Routing protocols in UAV swarm Ad Hoc networks can be divided into active routing protocols, such as optimized link state routing protocol (OLSR) and distance-vector routing protocol (DSDV), and on-demand routing protocols, such as Ad Hoc on-demand distance vector (AODV) and dynamic source routing (DSR). These routing protocols perform well in small and medium-sized flat-structured networks, but if they continue to use a flat-networked structure in a UAV swarm network with dense nodes, the network performance will become very poor. Therefore, it is necessary to study the hierarchical structure of the UAV swarm Ad Hoc network.

At present, many studies have been carried out to solve the problems. For clustering, a motion prediction mechanism based on prefix tree to cluster UAV swarm is proposed using global position system (GPS) to locate UAVs [4], which solves the problem of high mobility of UAV. Reference [5] proposed the node response mechanism and by calculating the link retention time, a more stable and secure clustering structure can be obtained which can prolong the lifetime of network. Deep Q-learning is used to perform clustering by optimizing the rewarding function in Markov process [6]. Based on the behavior pattern of bird flocks, the cluster nodes are divided into regions for clustering [7]. Only the nodes in the center of the region are qualified to participate in the clustering process according to the residual energy of the nodes, and this method can decrease energy loses and prolong network lifetime. For routing, by optimizing the selection of multipoint relay (MPR), OLSR got improved, which can reduce the packet loss ratio and delay [8]. An area-based route discovery mechanism and a link failure prediction mechanism are proposed to improve link stability [9]. To encrypt the communication, extra fields encrypted by hash function are added to the route request (RREQ) of the AODV protocol for identification, which improves the security of the network and decreases delay [10]. A trust determination mechanism combined with a fuzzy clustering algorithm is proposed, which can effectively lower the attack of malicious nodes [11]. Combining AODV with delay tolerant network (DTN) which can improve the performance of the network in scenarios with poor link stability [12]. However, UAV swarm Ad Hoc network with high density and mobility is different from traditional Ad Hoc networks. Dense nodes make it hard to establish the route and high mobility makes the communication link easily broken, dropping the packet deliver ratio (PDR) sharply. Therefore, we consider clustering and routing both. The purpose of clustering is to make the network as stable as possible and reduce route reconfiguration.

In this paper, we propose a hierarchical routing algorithm WBC-AODV. First, the network is clustered. The weighted-based clustering algorithm (WCA) of the UAV swarm proposed in this paper can effectively cluster the network. At the same time, the clustering algorithm requires less information interaction between UAVs, and information exchange can be realized by using the HELLO message. Then, this paper improves the AODV routing protocol, introduces the identity field for RREQ, and differentiates the ways of processing RREQ for nodes with different identities, so as to realize hierarchical routing. Finally, the clustering and routing algorithms are modeled and simulated. Compared with AODV, the method proposed in this paper has higher packet delivery ratio but also longer average end-to-end delay.

The remainder of this paper is organized as follows. In section II, the system model and transmission model of the UAV flight Ad Hoc network with hierarchical structure are introduced, and the method to be used in this paper is

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explained. In section III, we will give the principle and implementation process of the specific algorithm we proposed. In section IV, simulation configuration and performance analysis will be provided. Finally, the conclusion will be drawn in section V.

II. System Model

A. Hierarchical Structure UAV Ad Hoc Network

The system model of a typical hierarchical structure UAV Ad Hoc network is shown in Fig. 1. Clustering and routing are the two main problems that need to be solved in building a hierarchical structure UAV Ad Hoc network.

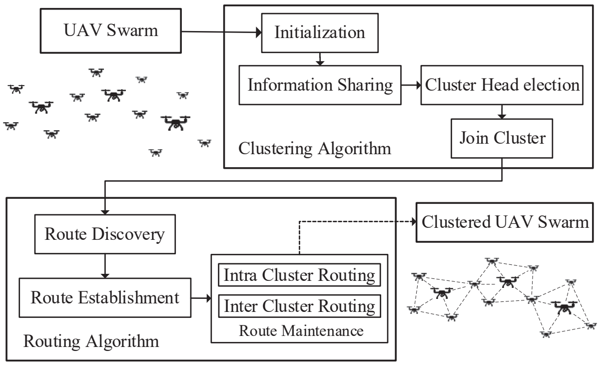


Fig. 1. Sketch of hierarchical structure UAV Ad Hoc network system

In order to manage UAVs hierarchically, the network needs to be clustered first. There are many types of clustering algorithms, and the weighted-based clustering algorithm (WCA) is mainly used in this paper. The weighted-based clustering algorithm is a general term for a class of algorithms. Usually, a variety of factors are used as the basis to quantitatively calculate the weight of the node, and the cluster head election is performed according to the weight. Commonly considered factors include node degree, mobility, energy, relative distance between nodes, etc. of UAVs. If there are multiple nodes with the same weight, the node with the smallest ID becomes the cluster head. The general weight calculation formula of this algorithm can be expressed as:

$$W_i = w_1 P_i + w_2 M_i + w_3 E_i + w_4 D_i \tag{1}$$

where w_1, w_2, w_3, w_4 are the weighting coefficients of node degree, mobility of the node, remaining energy of the node, and average distance respectively. At the same time, $w_1 + w_2 + w_3 + w_4 = 1$, and the specific value can be adjusted according to actual needs.

The factors considered in this algorithm are more comprehensive, and a more stable cluster structure can be obtained, but different factors will affect the performance of the hierarchical network, so the calculation of weight is the core of this part.

The routing algorithm is mainly responsible for finding a path for the UAV to communicate. Usually, the routing algorithm will use a certain variable as a criterion to select the optimal path. For example, the AODV routing protocol selects the path with the fewest hops. Some classic algorithms have better performance and lower complexity, but routing algorithms do not necessarily have the function of hierarchical routing, and these routing algorithms are less flexible in practical use. AODV has poor performance of packet delivery ratio (PDR) in large-scale networks, and does not have the function of hierarchical routing. This paper will improve AODV to make it suitable for use in UAV swarm networks.

B. Propagation Model

The transmission model is very important for wireless networks and needs to be analyzed in combination with actual usage scenarios. Considering that UAVs are usually used in outdoor environments and there are few obstacles that directly block the communication between UAVs, the transmission model adopts the free space propagation model commonly used in flying Ad Hoc networks (FANET). Communication can be established by any UAV that is separated by a distance not exceeding the communication distance. The formula of the free space propagation model can be expressed as:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{2}$$

where $P_r(d)$ is the received signal power, P_t is the transmit signal power, G_t and G_r are the transmit antenna gain and receive antenna gain respectively, λ is the wavelength, d is the Euclidean distance between the transmitter and receiver, and L is the system loss coefficient which can be calculated by (3)

$$L(\mathrm{dB}) = 32.45 + 20\lg f + 20\lg d \tag{3}$$

where f is the frequency. The unit of f is MHz, the unit of d is km.

III. Proposed Method

A. UAV Swarm Weighted-Based Clustering Algorithm

As a distributed clustering algorithm, WCA is quite suitable for Ad Hoc network. This paper improves the weight calculation method of WCA, and proposes a weighted-based clustering algorithm suitable for UAV swarms. The UAV swarm WCA proposed in this paper considers the influence of factors such as the degree of connection of nodes, the average distance and the remaining energy of nodes, and quantifies and weights various factors to calculate the weight. The clustering algorithm proposed in this paper is carried out within the neighbor nodes of the node. Represent the topology of a wireless network as an undirected graph $G, G = (V, E)$ where V is node set, E is edge set and both of them are finite set. Let the *i*-th node in the network be n_i, $\forall n_i, n_j \in V$, if there only one hop from n_i to n_j, then n_i and n_j are neighbor nodes to each other. $N(n_i)$ is set of neighbor node of n_i and can be expressed as:

$$N(n_i) = \{ n_j \mid dist(n_i, n_j) \le C_{\text{range}} \} \tag{4}$$

where C_{range} is the communication range of n_i.

After defining the neighbor nodes, the node degree d can be calculated by (5)

$$d(n_i) = |N(n_i)| \tag{5}$$

where $d(n_i)$ is the node degree of n_i.

There may be cases where a node does not have neighbor nodes, so an isolated node is defined. If a node does not have any neighbor nodes, it is called an isolated node.

On the basis of the node degree, the average node degree P is defined which is related to the number of neighbor nodes of the node and the number of neighbor nodes of the neighbor node [13]. The calculation of P is shown in (6)

$$P(n_i)=\frac{1}{d(n_i)+1}\left[d(n_i)+\sum_{n_j\in N(n_i)}d(n_j)\right] \tag{6}$$

Then the node degree difference Δ can then be calculated by (7), which is defined as the difference between the node degree and average node degree of a node.

$$\Delta(n_i)=1-\exp\left(-\left|d(n_i)-P(n_i)\right|\right) \tag{7}$$

The node degree difference will be used as one of the factors in calculating the weight. At the same time, the algorithm also considers the average distance between the node and its neighbor nodes. And the average distance D can be calculated by (8)

$$D(n_i)=\frac{1}{d(n_i)\times C_{\text{range}}}\sum\nolimits_{n_j\in N(n_i)}\left\{dist(n_i,n_j)\right\} \tag{8}$$

where $D(n_i)$ is the average distance between n_i and its neighbor nodes after normalization.

The average distance will be used as the second factor in calculating the weight. Also, in order to balance the energy consumption of UAVs and prolong the survival time of the network, the algorithm also considers the energy consumed by UAVs. Assuming that initially, the energy of each node is equal to E_S, the energy consumption of each node in the monitoring channel and the energy consumption of each forwarding message are respectively equal, and the node can obtain its own remaining energy E_R at each moment. Then the energy consumed by UAV at a certain time can be calculated by (9)

$$E(n_i)=(E_S-E_R)/E_S \tag{9}$$

where $E(n_i)$ is the energy consumption of n_i after normalization.

After calculating weighting factors all above, finally the weight of UAV can be calculated by (10)

$$W(n_i)=w_1\Delta(n_i)+w_2D(n_i)+w_3E(n_i) \tag{10}$$

where $W(n_i)$ is the weight of n_i, and $w_1+w_2+w_3=1$.

The cluster head election process in the weighted-based clustering algorithm we proposed is shown in Algorithm 1.

Algorithm 1 Proposed Clustering Algorithm

```
Define M(n_i) as the neighbor node map of n_i, the key of M is the
ID of its neighbor node, the value is the weight (W)
Define U as the set of UAVs
Calculate the weight (W) of all UAVs
for all n_i ∈ U do
  Sort M(n_i) by W in ascending order
  for j=1 to N(n_i) do
    if the key of M[j] is equal to the ID of then
      broadcast cluster head announcement
      n_i becomes cluster head
    end if
  end for
end for
```

After clustering, the nodes in the network are divided into cluster head nodes (CH) and cluster member nodes (CM). At the same time, we stipulate that if the cluster member node belongs to multiple clusters, the node becomes a forwarding node to connect the communication between clusters. In terms of maintenance mechanism, this paper selects periodic maintenance mechanism.

B. WBC-AODV Hierarchical Routing Protocol

The traditional AODV routing protocol is a flat routing protocol and does not have the function of hierarchical routing. This paper modifies the routing construction process of traditional AODV, so that it can realize hierarchical routing, and UAVs can establish correct routing according to the hierarchical structure. This paper modifies the format of the RREQ data packet in traditional AODV and adds a node identity field as shown in Fig. 2.

0 1 2 3 4 5 6 7	0	1	2	3	4	5 6 7 0 1 2 3 4 5 6 7	0 1 2 3 4 5 6 7
Type	J	R	G	D	U	Reserved	Hop Count
RREQ ID							
Destination IP Address							
Destination Sequence Number							
Originator IP Address							
Originator Sequence Number							
Node Identity							

Fig. 2. Modified RREQ frame format

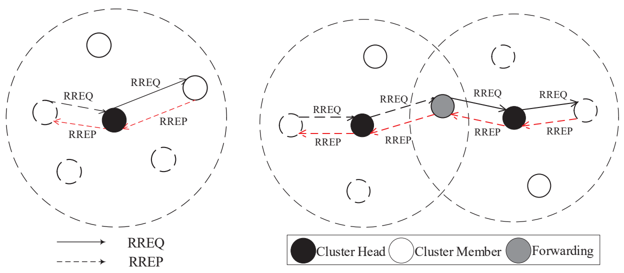
The WBC-AODV proposed in this paper stipulates that nodes with different identities have different message processing rights. Cluster member nodes can send data packets and receive data packets destined for themselves but cannot forward data packets. Both forwarding nodes and cluster head nodes can send, receive and forward data packets. Therefore, in the process of route establishment, nodes with different identities handle RREQ differently. The process of the RREQ after the node receives the RREQ is shown in Algorithm 2.

Algorithm 2 Proposed RREQ Processing Algorithm

```
if it has received a RREQ with the same originator IP and RREQ ID
then
  discard this RREQ
else if it is itself the destination then
  generates a RREP
  unicasts the RREP to the next hop
else if the identity of the node is cluster head or forward node then
  if it has an active route to destination then
    generates a RREP
unicasts the RREP to the next hop
  else
    forwards the RREQ
  end if
else
  discard the RREQ
end if
```

When the node receives the RREQ, it first checks whether there is a reverse route to the source node in the routing table. If it does not exist, it creates routing information immediately. If it exists, it continues to determine whether the route needs to be updated. Then judge whether it has received the same RREQ data packet from the same node, if so, discard it, otherwise continue to judge whether it is the destination node. If so, reply RREP to the source node through reverse routing, otherwise continue to judge whether it is a cluster head or a forwarding node. If not, the node will directly discard the received RREQ. If so, it will judge whether there is valid routing information to the destination node in its own routing table. If so, the node returns the RREP to the source node, otherwise it increases the hop count by one and continues to forward the RREQ.

The routing table needs to manage the route intra-cluster and route inter-cluster as shown in Fig. 3. When a cluster member send RREQ to find the route to a node intra-cluster, if the destination node is out of the communication range of itself, the cluster head node needs to participate to complete the packet forwarding. Fig. 3(a) shows the process of routing establishment intra-cluster. The destination node is out of the communication range of the originator node and the cluster head will forward the RREQ from the originator while other will discard it. But if the destination node is within the communication range of itself, then the node can directly establish communication with the destination node without the help of the cluster head. When a cluster member needs the route to a node inter-cluster, it can initiate a routing request outside the cluster with the help of the cluster head or the forwarding node, while other cluster member nodes will not participate in the process. Fig. 3(b) shows the process of routing establishment inter-cluster. Only the cluster head and forwarding node will forward the RREQ from the originator node. Therefore, using the routing algorithm proposed in this paper can reduce a large number of repeated RREQ packets in the network improving the performance of the network.



(a) Intra-cluster routing (b) Inter-cluster routing

Fig. 3. Routing establishment of WBC-AODV

IV. Implementation and Performance Analysis

A. Experiment Setup

In order to simulate the proposed algorithm, we use OMNeT++ for experimental simulation. OMNeT++ is an object-oriented, modular, time-distributed network simulation framework, which is widely used in the simulation of wireless communication networks. It is easy to observe the changes of network topology and has good visualization performance, which is very suitable for the algorithm simulation proposed in this paper.

This paper uses OMNeT++ to simulate the AODV routing protocol and the WBC-AODV routing protocol. We generate different scenarios , run simulations for each scenario multiple times, and finally analyzes the performance of the two routing protocols. Weighting coefficients in (10) are assumed: $w_1 = 0.4$, $w_2 = 0.4$ and $w_3 = 0.2$. The simulation parameters are set as shown in TABLE I. Random waypoint (RWP) which is commonly used in the simulation of FANET is selected as the motion model.

TABLE I. Simulation Parameters

Parameters	**Value**
Simulation area	1000m×1000m
Number of UAVs	70
Motion model	Random Waypoint
MAC protocol	IEEE 802.11
Simulation time	120s
Traffic type	CBR
Packet size	512Byte
Maximum velocity	5-30 m/s

B. Experiment Results

This paper mainly evaluates the performance of the routing protocol from the packet delivery ratio (PDR) and the average end-to-end delay. The calculation formulas of the PDR and the average end-to-end delay are (11) and (12) respectively.

$$PDR = \frac{count(\text{packet\_received})}{count(\text{packet\_sent})} \tag{11}$$

$$avg\_delay = \frac{\sum_i \left(T_{\text{received}}(i) - T_{\text{sent}}(i)\right)}{count\left(T_{\text{sent}}(i)\right)} \tag{12}$$

In order to observe the performance of the two protocols of UAV at different velocity, we changed the velocity of the UAV for multiple simulations, and obtained the simulation results shown in Fig. 4 and Fig. 5.

Fig. 4 shows the simulation result of PDR under different UAV velocity. And average statistic value of PDR for tow protocols is listed in TABLE II.

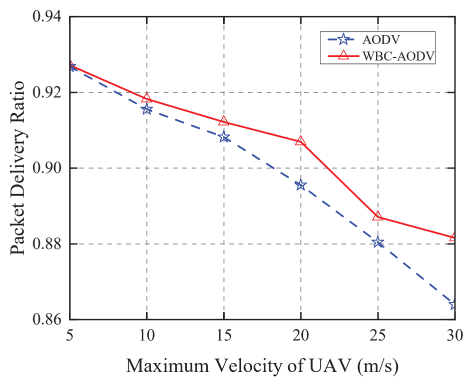


Fig. 4. Packet delivery ratio under different UAV velocity

TABLE II. Statistic Value of PDR under Different Velocity

Maximum Velocity of UAV (m/s)	**Packet Delivery Ratio**	
	AODV	**WBC-AODV**
5	0.92678	0.92717
10	0.91552	0.91827
15	0.90823	0.91216
20	0.89552	0.90693
25	0.88041	0.88705
30	0.86394	0.88153

PDR is mainly used to evaluate the reliability of the network, which is very important to the performance of the network and is one of the most important indicators. When the node mobility is low, there is little difference in performance between the two routing protocols. With the increase of node speed, the PDR of WBC-AODV is higher. This is because the backbone network formed by clustering is more stable. At the same time, this hierarchical structure reduces the control information that needs to be forwarded repeatedly in flood routing, reducing the probability of packet collisions, thereby improving the PDR. In practice, the moving speed of the UAV Ad Hoc network is relatively fast, so after the moving speed is greater than 20m/s, the protocol proposed in this paper improves the packet delivery ratio by about 1%~2% compared with the traditional AODV.

Fig. 5 shows the simulation result of average end-to-end delay under different UAV velocity.

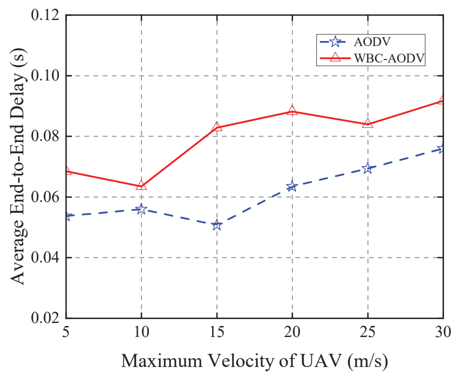


Fig. 5. Average end-to-end delay under different UAV velocity

The average end-to-end delay is mainly used for the effectiveness of the network. Usually, if the service does not require high real-time performance, the requirements for the delay are not particularly high. With the increase of node speed, the average end-to-end delay of both routing protocols increases. WBC-AODV still takes the hop count as the routing cost, and the route hop count is positively correlated with the delay at this time. Due to the limitation of the hierarchical structure, WBC-ADOV may find that the number of hops of the path found when establishing a route may be greater than the number of hops of the shortest path, so the average end-to-end delay is ultimately higher than that of the traditional AODV protocol. However, the delay of the algorithm proposed in this paper is still at a low level, and the impact on the network is small, which can meet the needs of most scenarios.

V. Conclusion

Due to the performance of packet delivery in the UAV swarm network is poor under the traditional method. This paper optimizes the weight calculation of the weighted-based clustering algorithm, designs a clustering algorithm suitable for the UAV swarm Ad Hoc network, and proposes a hierarchical routing protocol WBC-AODV based on the clustering structure combined with the AODV routing protocol. The simulation shows that compared with AODV, WBC-AODV can improve the packet delivery ratio by about 1%~2% when the UAV is more mobile, but due to the limitation of hierarchical structure, it has a higher average end-to-end delay. However, it can still meet the needs of most scenarios.

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