A Novel Cluster-Based Location-Aided Routing Protocol for UAV Fleet Networks

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Abstract

With the extensive applications of unmanned aerial vehicle (UAV), there is an urgent need for building UAV fleet networks to enhance the overall operational efficiency, in which the architecture of mobile Ad Hoc network (MANET) should be adopted. In this paper, we propose a novel routing protocol to address the issues of routing in UAV fleet networks, referred to as Cluster-Based Location-Aided Dynamic Source Routing (CBLADSR). CBLADSR forms stable cluster architecture of UAV fleet as the basis and then performs route discovery and route maintenance by using the geographic location of UAVs. The clustering process utilizes Node-Weight heuristic algorithm to elect cluster heads and form clusters, while the routing process is a combination of Intra Cluster Routing and Inter Cluster Routing, which employs short-range transmission and long-range transmission respectively. Simulation results have shown that CBLADSR outperforms DSR and GRP significantly in successful delivery ratio and average end-to-end delay, as well as in scalability and dynamic performance, which make it more suitable to be applied in UAV fleet networks.

Keywords: UAV Fleet Networks, MANET, Clustering Algorithms, Routing Protocols, Scalable Routing

1. Introduction

In recent years, with the advantages of light weight, small size, high flexibility, low price, zero casualties, etc., unmanned aerial vehicles (UAVs) have been extensively engaged in military fields, as well as in national economy. As indicated by the U.S. Army Unmanned Aircraft Systems Roadmap 2010–2035, the US Air Force employs UAVs mainly for reconnaissance, surveillance, battle damage assessment, and direct attack missions [1]. However, the limited energy, short transmission range, and simple functions of single UAV restrict its further applications, insufficient to meet the various demands of the Army. Therefore, there exists an urgent need for building UAV fleet networks to improve the overall operational efficiency through the cooperation of multiple UAVs. UAV fleet network achieves information sharing and data exchange through the reliable, real-time, and high-speed communication between UAVs. The construction of UAV fleet network would effectively enhance the work efficiency, controllability, survivability, and anti-jamming capability of UAV fleet, thus improve the tactical effectiveness and extend the scope of applications. UAVs usually work in complex and changing environment with flexible operational manners and high mobility; therefore, it is necessary to apply the architecture of mobile Ad Hoc network (MANET) in the design of UAV fleet network.

In this paper, we propose a novel routing protocol for UAV fleet networks by using the location information of UAV nodes based on the cluster architecture of UAV fleet, referred to as Cluster-Based Location-Aided Dynamic Source Routing (CBLADSR). In brief, our approach is to form stable cluster architecture of UAV fleet network as the basis for routing and then to perform route discovery and route maintenance by using the geographic location of UAV nodes. The cluster head (CH) election is based on Node-Weight heuristic algorithm, which assigns node weights according to the suitability of nodes acting as CHs, by taking the connectivity degree, relative speed, residual energy, and weapon and equipment into consideration. After the cluster architecture has been formed, the proposed routing protocol is performed distributedly. In CBLADSR, CHs employ Location-Aided Dynamic Source Routing (LADSR) for Inter Cluster Routing using long-range transmission, while cluster members (CMs) take on roles of Intra Cluster Routing using short-range transmission. With the cluster architecture and limited forwarding domain, nodes involved in route discovery and route maintenance are reduced dramatically, which results in less routing overhead and end-to-end delay. Theoretical
analysis and simulation results show that the proposed clustering algorithm and routing protocol are highly efficient, scalable, and suited for UAV fleet networks.

The rest of this paper is organized as follows. Section 2 introduces related clustering algorithms and routing protocols. Section 3 describes the cluster-based UAV fleet network architecture. Section 4 presents the proposed CBLADSR protocol. Section 5 presents the comparative performance evaluation of CBLADSR to Dynamic Source Routing (DSR) and Geographic Routing Protocol (GRP) on OPNET Modeler. The conclusion is given in Section 6.

2. Related work

In recent years, to organize the network into hierarchical structure, many clustering algorithms have been proposed for MANET. Lowest-ID with Adaptive ID Reassignment (LIDAR) [2] forms clusters based on the time and cost-efficient lowest-ID method, and reassigns node IDs according to node mobility and energy status during the cluster maintenance phase. MOBIC [3] is a distributed clustering algorithm where each node calculates relative mobility values with respect to the neighboring nodes for the CH selection. Weighted Clustering Algorithm (WCA) [4] is a weight metric-based clustering approach which takes into consideration the ideal degree, transmission power, mobility, and battery power of mobile nodes. As a modification suggested to WCA, Weight Based Adaptive Clustering for Large Scale Heterogeneous MANET (WACHM) [5] incorporates node heterogeneity and scalability in the algorithm design.

On the basis of the cluster architecture, there have been a number of hierarchical routing protocols proposed for MANET. Cluster Based Routing Protocol (CBRP) [6] divides nodes into overlapping or disjoint 2-hop-diameter clusters in a distributed manner, by which the protocol speeds up the route discovery process and minimizes the flooding traffic. Virtual Structure Routing (VSR) [7] is based on a virtual topology including both a backbone and clusters; VSR combines the assets of both flat approaches: intra-cluster routing is proactive while inter-cluster routing is reactive. There are also a few hierarchical routing protocols proposed to increase the scalability of the network by reducing the control overhead [8], [9].

Routing protocol has been a major research topic in Ad Hoc networks [10]–[13]. Location-aware routing, also known as geographic routing, which relies on location and mobility information, has also received much attention in recent years [14]–[16]. However, the research of location-aware routing on the basis of hierarchical structure is still in its infancy. Cluster Based Location-Aware Routing Protocol for Large Scale Heterogeneous MANET (CBLARHM) [17] incorporates cluster architecture and location-aware routing to achieve low routing overhead, high success delivery ratio, and low average end-to-end delay. Location-Aided Hierarchical Cluster Routing (LHCR) [18] takes location factor into account to form n-level cluster structure, then performs proactive intra-cluster routing and reactive inter-cluster routing, which are taken care of by the node of the highest level in each cluster.

There have been some preliminary researches on routing in UAV fleet networks. In [19], Alshbatat develops Directional Optimized Link State Routing (DOLSR) so that the decision for selecting the route will be based on a local profile that holds the gathered information of UAV, which significantly reduces the overhead packets in comparison with OLSR. In [20], Shirani explores the effects of network sparsity on the performance of greedy geographic forwarding and shows that the protocol can be used for less critical applications of UAV fleet networks.

3. Cluster-based UAV fleet network architecture

According to the requirements of battlefield applications, UAV fleet carries out missions in the form of formation, which consists of two types of UAVs: lead UAV and task UAV. Task UAV performs specific tactical tasks such as reconnaissance, electronic countermeasure, and direct attack; while lead UAV takes the responsibility of coordinated communication and management of the formation as well. Compared to task UAV, lead UAV has more initial energy, less relative mobility, and longer transmission range, which make it more suitable to be CH. Therefore, the CH election is mainly carried out among lead UAVs.

Based on the battlefield environment and operational requirements, in the process of CH election, four system parameters of UAV nodes should be taken into consideration: (a) connectivity degree $C$, (b) location, (c) remaining energy, and (d) mobility.
which indicates the number of one-hop neighbors; (b) relative speed $S$, which indicates UAV’s relative mobility to the formation; (c) residual energy $E$, which indicates the energy situation of UAV; (d) weapon and equipment $T$, which indicates the tactical value of UAV. In this paper, we make a reasonable assumption that all UAVs are equipped with GPS or other positioning systems. With the location information provided by GPS, UAV nodes learn the local network topology, and distributedly determine the above system parameters through the information exchange and sharing within the formation. We adopt Node-Weight heuristic algorithm to assign node weights, by applying (1):

$$W_{node} = w_1 C + w_2 S + w_3 E + w_4 T$$

(1)

where $w_1$, $w_2$, $w_3$, and $w_4$ are weight factors determined by the application scenarios of UAV fleet network, which satisfy the normalized formula:

$$w_1 + w_2 + w_3 + w_4 = 1$$

(2)

In the clustering process, only lead UAVs participate in CH election, except for the situation that there are no lead UAVs in the formation. On the premise of satisfying the residual energy threshold, the candidate UAV with the largest weight in the formation becomes CH and broadcasts CH declaration message, while other UAVs in the formation reply to the CH and become CMs. Due to the high risk and complexity of battlefield environment, the candidate UAV with the second largest weight, if exists, is chosen as backup CH, which will quickly take the roles of CH when current CH is not eligible. In the formation without lead UAVs, which is rare case, task UAVs will participate in CH election and may become temporary CH until lead UAVs enter the formation.

To store basic information and necessary data, each UAV maintains a cluster information table. As for CM, the information table consists of two child tables: (a) Status Table, which keeps the node’s basic information; (b) Neighbor Table, which stores the location information of one-hop neighbor nodes. As for CH, the information table consists of four child tables: (a) Status Table, as described above; (b) CM Table, which stores the basic information of CMs in the cluster; (c) CH Table, which stores the location information of all CHs in the network; (d) Temp Table, which stores the basic information of temp members occurred accidentally in the cluster. With the cluster information table, the cluster architecture is highly adaptive to network topology changes, in this way speeds up the process of cluster maintenance.

4. Design issues of CBLADSR protocol

Based on the cluster architecture described in the previous section, we propose a novel CBLADSR protocol to address the issues of routing in UAV fleet networks. CBLADSR is a combination of Intra Cluster Routing and Inter Cluster Routing, hence a hierarchical routing protocol. Intra Cluster Routing is performed based on the Neighbor Table of each node, hence a Table-Driven routing method. When a node wants to send packets to another node in the same cluster, it simply looks up the Neighbor Table to learn the location information, and directly sends packets towards the destination node using short-range transmission. Inter Cluster Routing employs the proposed LADSR, which is a location-aware protocol based on DSR. When the destination node is present in a different cluster, the source node sends packets to its CH using short-range transmission. Source CH looks up its CH Table to learn the location information of CH which the destination node belongs to, and sends packets towards the adjacent CH which is the nearest to the destination CH using long-range transmission. If destination CH is away from source CH by more than two clusters, in which case the location information is not precise enough, the source CH sends a route request packet to all CHs in the direction of destination CH. On receiving the route request packet, the destination CH sends back a route reply packet to inform source CH. On receipt of the route reply packet, source CH sends data packets along the discovered route. Finally, destination CH forwards data packets to the destination node using short-range transmission, thus completes the Inter Cluster Routing process. Fig. 1 illustrates the routing process of CBLADSR protocol, which presents both the Intra Cluster Routing and Inter Cluster Routing.
To reduce the traffic of route request and the probability of collision, in this paper, we define the expected zone and request zone based on the assumptions described in Location-Aided Routing (LAR). We extend the expected zone in LAR by taking the time interval $\Delta t$ into account, which is the estimated transmission time from source to destination. Therefore, the radius of expected zone can be given as $v_D[(t_1 - t_0) + \Delta t]$, where $v_D$ is the speed of destination node, $t_1$ is the current time, and $t_0$ is the last time source node obtained location information. As for the request zone, we restrict the propagation of route request packets into a smaller forwarding zone compared to LAR Scheme 1, by taking three scenarios into consideration: (a) source is outside of expected zone, while source and destination are in same cluster; (b) source is outside of expected zone, while source and destination are in different clusters; (c) source is within the expected zone. The detailed configurations of request zone are similar to those described in [13]. When confronting the hole problem, CBLADSR applies the slope-based forwarding strategy, which selects the neighbor with the minimum slope as the next-hop node.

![Figure 1. The routing process of CBLADSR protocol](image)

There are some further instructions of our proposed CBLADSR protocol. Firstly, there are no gateway nodes in the cluster architecture of UAV fleet network with the introduction of long-range transmission. Therefore, CMs are not related to the routing process unless they are source or destination themselves, which dramatically reduces the routing overhead. Secondly, if the source and destination are neighbors while they are in adjacent clusters, the hierarchy can be ignored temporarily, which means that the source can send packets to destination directly without passing through CHs. This method, referred to as Neighbor Routing, could greatly improve the efficiency of CBLADSR protocol. As shown in Fig. 1, UAV 11 directly sends packets to UAV 28 by the method of Neighbor Routing; otherwise the routing path will be much longer. Finally, the route maintenance process of CBLADSR will be followed by DSR protocol with location-aiding, similar to the route discovery process described above.

5. Simulation setup and result analysis

In this section, the performance of the proposed CBLADSR is evaluated and compared to DSR and GRP on OPNET Modeler. We carry out two scenarios of comparative simulations: (a) Node number scaling scenario, in which we scale up the number of nodes while varying the size of network to study the scalability of routing protocols. We carry out four sets of simulations in geographic areas: size 2,
000m × 2, 000m with 25 nodes, size 3, 000m × 3, 000m with 50 nodes, size 4, 000m × 4, 000m with 75 nodes, and size 5, 000m × 5, 000m with 100 nodes, while the node speed is fixed at 30m/s. (b) Node speed varying scenario, in which we change the speed of nodes to study the dynamic characteristics of routing protocols. We carry out six sets of simulations in a fixed area of size 3, 000m × 3, 000m with 50 nodes, while the node speed is set to 10, 20, 30, 40, 50, and 60m/s, respectively. We also consider the group mobility characteristics of UAV fleet, such that nodes in the same geographic zone are endowed with close velocity and direction of motion at the beginning of simulation, and the change of velocity and direction when reaching the default destination will be conducted in similar ways. The simulation parameters are summarized in Table 1.

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network model</td>
<td>MANET</td>
</tr>
<tr>
<td>MAC protocol</td>
<td>IEEE 802.11</td>
</tr>
<tr>
<td>Mobility model</td>
<td>Improved random waypoint</td>
</tr>
<tr>
<td>Pause time</td>
<td>0 sec</td>
</tr>
<tr>
<td>Packet inter-arrival time</td>
<td>1 sec, poisson</td>
</tr>
<tr>
<td>Packet size</td>
<td>1, 024 bits, constant</td>
</tr>
<tr>
<td>Channel capacity</td>
<td>2 Mbps</td>
</tr>
<tr>
<td>Task UAV. initial energy</td>
<td>150 J</td>
</tr>
<tr>
<td>Lead UAV. initial energy</td>
<td>300 J</td>
</tr>
<tr>
<td>Weight factors</td>
<td>( w_1 = 0.4; w_2 = 0.2; w_3 = 0.3; w_4 = 0.1 ).</td>
</tr>
<tr>
<td>Short transmission range</td>
<td>500 m</td>
</tr>
<tr>
<td>Long transmission range</td>
<td>1, 200 m</td>
</tr>
<tr>
<td>Simulation time</td>
<td>600 sec</td>
</tr>
</tbody>
</table>

To evaluate the routing performance of the proposed CBLADSR as well as DSR and GRP, we introduce two key performance metrics: (a) Successful delivery ratio, which is the ratio of data packets delivered to the destination node to those generated by the source node. (b) Average end-to-end delay, which is averaged over all surviving data packets from the source node to destination node. We perform four sets of comparative analyses for different scenarios and performance metrics, as follows.

Figure 2 shows the results of successful delivery ratio in the node number scaling scenario. It illustrates that the successful delivery ratios of all three routing protocols decrease with the increase in number of nodes, while the proposed CBLADSR outperforms DSR and GRP in networks of all sizes, especially in large-scale networks. CBLADSR forms stable cluster architecture and performs location-aided routing in a smaller estimated area, thus possesses high successful delivery ratio and good scalability. DSR and GRP are flat routing protocols with poor scalability, which leads to low successful delivery ratio when the network size scales up.

![Figure 2. Successful delivery ratio with varying the number of nodes](image)

Figure 3 shows the results of average end-to-end delay in the node number scaling scenario. The average end-to-end delay of all routing protocols increases when scaling up the node number, while CBLADSR performs better than DSR and GRP in networks of all sizes. The reason is that CBLADSR
performs Intra Cluster Routing based on the Neighbor Table, and performs Inter Cluster Routing between CHs using long-range transmission, which significantly reduce the network latency. CBLADSR reduces the delay caused by packets waiting for route discovery compared to DSR, while reduces the delay due to calculating the route to next-hop node compared to GRP, which result in lower average end-to-end delay as well as good scalability.

Figure 3. Average end-to-end delay with varying the number of nodes

Figure 4 shows the results of successful delivery ratio in the node speed varying scenario. It illustrates that the successful delivery ratios of all routing protocols decrease when increasing the node speed, which is due to frequent changes of network topology caused by high mobility. However, CBLADSR still has advantage over DSR and GRP with the stable cluster architecture. In CBLADSR, Intra Cluster Routing can be guaranteed even in high mobility situations, while the influence on Inter Cluster Routing is mitigated by the long-range transmission scheme of CHs, which result in relative stable performance when confronting high mobility.

Figure 4. Successful delivery ratio with varying the speed of nodes

Figure 5 shows the results of average end-to-end delay in the node speed varying scenario. In general, the average end-to-end delay is on the decline for all three protocols when nodes speed up. The reason is that the number of total packets received by destination nodes decreases dramatically as node speed increases, while the source-destination pairs are relatively close to each other, as a consequence, the end-to-end delay declines. Overall, CBLADSR possesses a relatively good latency performance compared to other protocols. However, CBLADSR performs worse than GRP in network latency under the situation with the highest speed, which can be explained by more long-distance packet transmission due to relatively high packet delivery ratio between the clusters.
6. Conclusion

In this paper, we propose a novel CBLADSR protocol to address the issues of routing in UAV fleet networks. CBLADSR performs route discovery and route maintenance based on the cluster architecture of UAV fleet with the aid of location information. The clustering process is based on Node-Weight heuristic algorithm, which assigns node weights according to connectivity degree, relative speed, residual energy, and weapon and equipment as the basis for electing CHs and forming stable clusters. The routing process is a combination of Intra Cluster Routing and Inter Cluster Routing, in which CHs employ LADSR, a location-aware protocol on the basis of DSR, to perform routing between the clusters by using long-range transmission; while CMs route packets within the clusters based on the Neighbor Table by using short-range transmission. Simulation results have shown that our proposed CBLADSR outperforms DSR and GRP significantly in successful delivery ratio and average end-to-end delay, as well as possessing good scalability and dynamic performance, which make it more suitable to be applied in UAV fleet networks and other high-dynamic large-scale MANETs.

7. References


