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# Topology Control Method for UAV Clusters Based on the Virtual Backbone Network

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**Abstract.** UAV cluster is a powerful tool for the effective execution of complex tasks in the era of intelligence, and the merits of the cluster network topology control method directly affect the performance of the network and the efficiency of cluster task execution. In this paper, a distributed cluster virtual backbone network construction algorithm (DCBNCA) is proposed for the topology control of the UAV cluster network. In this particular approach, the construction of the neighbor set for each node is accomplished through broadcasting instructions. Furthermore, a weight function is designed for network edges, considering physical attributes such as node degree, energy, and bandwidth. The final virtual backbone network is obtained by establishing connectivity based on the weight values within the independent set of the network. This process enables rapid convergence for topology control. Empirical results indicate that the aforementioned algorithm effectively manages the topology of UAV cluster networks, exhibiting significant performance improvements when compared to the original algorithm.

**Keywords.** Cluster topology control, Weight function, Virtual Backbone

## 1. Introduction

Modern warfare is prevailing towards the integration of sea, land, air, and sky multiple parties. Broadband data chains have become an important medium in the contemporary battlefield. Due to the rapidly changing battlefield environment, various factors such as forward systems can lead to system damage resulting in frequent changes in transmission data chain topology. Therefore, the establishment of virtual backbone networks proves to be an effective approach for simplifying data chain routing, resulting in improved utilization of system network resources [1-2]. Wireless Sensor Networks (WSNs) are decentralized sensing networks composed of multiple sensor nodes [3-4]. Given the limited battery capacity of these nodes, continuous operation is not feasible. Therefore, energy conservation methods are of paramount importance and serve as a significant research focus within the realm of wireless sensor networks. Virtual Backbone Network (VBN) divides the nodes in the network into a backbone node set and an ordinary node set, the backbone nodes act as relay nodes in the network to complete the task of message transmission during communication, and the non-backbone nodes are usually in dormant form, which are responsible for sending this node data monitoring. VBN improves the routing efficiency of the network by restricting the routing task to the backbone nodes,

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which effectively reduces the energy consumption in network operation. The main method for constructing VBNs is the Connected Dominating Set (CDS), and smaller VBNs can ensure higher communication efficiency. Genetic Algorithm is a heuristic search algorithm that draws inspiration from the principles of natural selection and genetics to solve optimization problems, where the fitness factor of each chromosome is obtained from the initial population calculation of GA chromosomes, and the chromosomes with high fitness are screened and bred. Only chromosomes with higher fitness scores survive in the newly bred progeny and eventually converge to obtain the optimal solution. The chromosome consists of many genes, and each gene in the chromosome is mapped to a node in the network, and the chromosome in the algorithm represents the possible CDSs in the network. In the context of energy conservation in Wireless Sensor Networks (WSNs), the construction of a Minimum Connected Dominating Set (MCDS) emerges as a crucial problem. To address this challenge, [5] proposes a distributed greedy approximation method specifically designed for building a minimum connected dominating set. This approach focuses on achieving the construction of random and uniformly distributed CDSs of nodes at a low cost. Additionally, [6] introduces an improved collaborative coverage algorithm to effectively solve the maximum independent set problem, resulting in notable enhancements in coverage efficiency.

## 2. Basic Theory

### 2.1 Complex graph theory

The communication network topology of a UAV formation under formation maintenance can be represented by a weighted directed graph $G=(V,A,W)$ . $V=\{\mathrm{v_i}\}$, $\mathrm{i}\in\{1,2,\cdots,\ \mathrm{n}\}$ is the set of points of the directed graph, and $E_0$ represents $UAV_i$. In the set of arcs of a directed graph, $A=\{\mathrm{a_{ij}}\}$ i, $\mathrm{j}\in\{1,2,\cdots,\ \mathrm{n}\}$, $\mathrm{i}\neq\mathrm{j}$, where $a_{ij}$ represents the communication link between $UAV_i$ and $UAV_j$ , $W=\{\mathrm{w_{ij}}\}$ , i, $\mathrm{j}\in\{1,2,\cdots,\ \mathrm{n}\}$, $\mathrm{i}\neq\mathrm{j}$ is the set of weights of all arcs of the directed graph, and $W_{ij}$ represents the weight of the communication link $\mathrm{a_{ij}}$.

Spanning tree: For an undirected graph G, a spanning subgraph T that forms a tree is called a spanning tree of G. Minimum spanning tree: Given a weighted undirected graph G, there exists a spanning tree T whose weights of all arcs and $W(T)$ are minimum, and then T is said to be the minimum spanning tree of G. The minimum spanning tree of a directed graph is called the minimum tree graph, and both the information interaction topology and the communication network topology under queueing holdings can be represented by the assigned directed graph. Dominating set considers a subset D of the graph $G(V,A)$ vertex set V(G). When any vertex that does not belong to the set D has at least one neighboring vertex that belongs to D, then D is said to be a dominating set of graph G.

Minimum dominating set: The minimum dominating set of a graph G is defined as the subset of vertices with the smallest cardinality that can dominate the entire graph. The corresponding fixed value representing the size of this set is referred to as the dominating number of the graph G, denoted as $\gamma(G)$.

## 3. Algorithm Description

This chapter describes the design of the review weight function that takes into account the node degree, bandwidth and energy, and also gives the specific design process of the virtual backbone network algorithm, including the two steps of neighbor set construction and great independent connectivity set construction of the cluster network.

### *3.1 Weight function design*

In a clustered network, a reasonable and effective selection of greatly independent and centralized dominating nodes is an important prerequisite for improving network transmission capacity, routing efficiency, and network life cycle. The selection principle of the dominant node should consider how to improve the above performance. The bandwidth of a node is a concrete manifestation of time-frequency resources, and a larger bandwidth can improve the information transmission rate, while a small bandwidth often causes network congestion or high delay. At the same time, the energy situation of nodes has always been a problem that self-organizing networks must focus on. Uniform energy consumption is an important way to extend the overall life cycle of the network, so selecting nodes with more remaining energy to be utilized is in line with the energy utilization rules for rapid changes in cluster network topology. As for the network, its routing efficiency determines the existence value of the network. Although the advanced multiplexing method makes the nodes have efficient information carrying efficiency, too many node degrees will cause larger network congestion, resulting in higher BER of the network. Therefore, taking into account the node degree, energy, and bandwidth issues of the cluster network at the same time is fundamental to achieving effective control of the topology, and the composite weight function designed in this paper is shown in Eq. (1).

$$\begin{gathered}Q(i)=\omega_1\left(\frac{B_i^t}{B_{\max}}\right)^2+\omega_2\left(\frac{d_i^t}{D_{\max}}\right)^2+\omega_3 e^{s_i/s_{aver}}\quad i=1,2,\ldots,N\quad \omega_1+\omega_2+\omega_3=1\\ s_{aver}=\sum_i^N s_i/N\end{gathered}\tag{1}$$

where $\omega_1,\omega_2,\omega_3$ are the weight coefficient of the weight function. The importance of a physical quantity can be changed by adjusting its size. $B_i^t$ is the real-time bandwidth of node $i$, $d_i^t$ is the degree case of node $i$, $s_i$ is the current energy profile of node $i$, $B_{\max}$ is the maximum bandwidth limit of the node, $D_{\max}$ is the maximum degree limit of the node, and $s_{aver}$ is the average of the energy of the network nodes. The nodes selected by this composite function can show better overall communication capability in terms of degree, bandwidth, and residual energy.

### *3.2 Algorithm specific implementation*

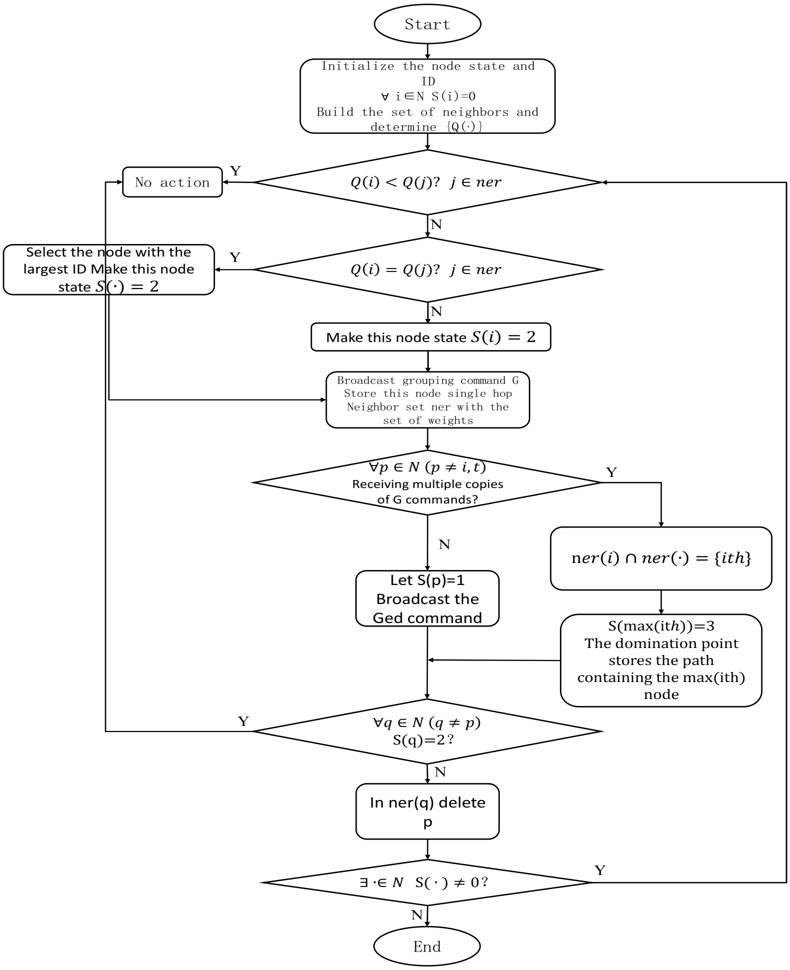

**Figure 1.** Flow Chart

It is supposed that there are N drones in the UAV cluster network and each drone exists with a unique ID number. The drone cluster first executes the first step of the algorithm to build the set of neighbors of the cluster network and obtain the corresponding set of composite weight functions $\{Q(\bullet)\}$. Each UAV will send HELLO commands to each other and store the weight value $Q(\bullet)$ and ID number of each node interactively, so that each UAV determines its own set of neighbors and the set of neighbor weights. We let $ner(i)$ be the set of neighbors of node $i$. $\{Q(i)\}$ is the set of neighbor weights of node $i$, and $S(\bullet)$ is the state representation function of the UAV, in which there exist four state values of $S(\bullet)$, 0, 1, 2 and 3, where 0 state is the initial state for marking the topology construction, 1 state is the dominated state, 2 state is the dominant state, and 3 state is the composite 1, 2 state, which is characterized according to 1 state during domination point construction and 2 state during connectivity construction. The specific flow of the very large independent connected set construction is as follows.

Step 1: $\forall i \in N$ We initialize each node in the network to state 0, while each node sends a HELLO command to obtain the set of neighbors while putting their respective weight values into the command for interaction to obtain the set of neighbor weights;

Step 2: We determine whether there is a node greater than its own weight in the set of neighbors of node $i$. If it exists, the network node has no action. Otherwise, we judge whether there is a node equal to its own weight in the neighbor set of node $i$. If it exists, we select the node $t$ with the largest ID number as the dominant node and update its state $S(t)=2$. Otherwise, we make itself the dominant node and update its state. At the same time, the node with state $S(i)=2$ broadcasts the G command signal and packs the current set of its own neighbors with the corresponding set of weights into the G command signal for broadcast;

Step 3: If node $p(p \neq i,t)$ receives multiple copies of the G command signal, we update $S(\bullet)=3$ with the node state after the intersection and store the node and link corresponding to the maximum value of the weights. Otherwise, we update node state $S(p)=1$ and send the Ged command signal;

Step 4: $\forall q \in N(q \neq p)$ We determine whether its status is 2. If yes, then the node has no action, otherwise remove $p$ from its neighbor nodes;

Step 5: For the whole network determine whether there is a 0-state node, if it exists, we return to step 2, otherwise the virtual backbone network construction is completed.

The flow chart representing the aforementioned steps is shown in Figure 1.

The construction process of the virtual backbone network based on the algorithm proposed in this paper is visualized in Figures 2, 3 and 4. Figure 2 displays the initial topology of the cluster network following the creation of the neighbor set. Figure 3 and Figure 4 show the process of simultaneous construction, but the two parts of the schematic process are shown separately for clarity. The set formed by the black nodes in Figure 3 is the greatly independent set, the blue nodes in Figure 4 are the intermediate nodes that make the greatly independent set connected, and the deepened nodes in Figure 4 together with the edges form the virtual backbone network.

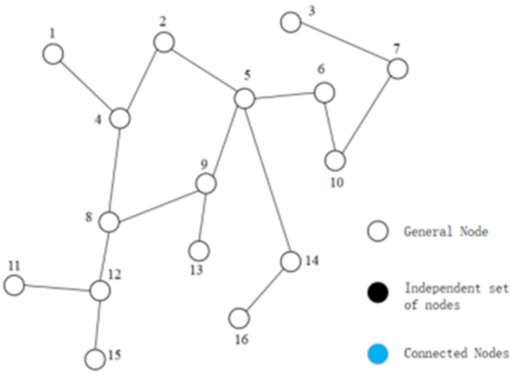

**Figure 2.** Initial topology of the clustered network

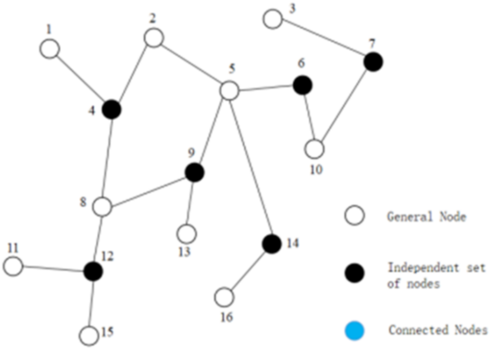

**Figure 3.** Unconnected greatly independent set

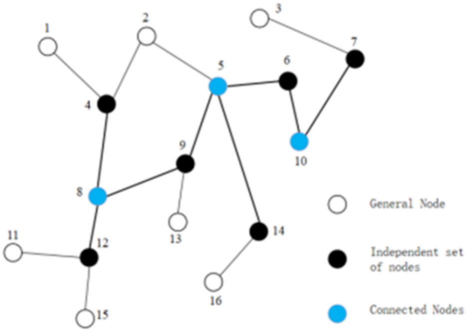

**Figure 4.** Connected to a great independent set

### *3.3 Algorithm Complexity Analysis*

In terms of complexity analysis of algorithms, this paper compares some relevant algorithms in terms of time complexity and message complexity. We assume that the number of dominating nodes is $N'$ . For time complexity, each UAV executes the algorithm in parallel, and each UAV performs topology construction with at most N-1 UAVs, so the time complexity of the algorithm presented in this paper can be expressed as O(N). As for the message complexity, there are 2 N broadcast interactions for each UAV during the initial neighbor set construction, and later, due to the merging of the algorithm of the greatly independent set with its connectivity, the process of connectivity has been stored for interaction when the dominating node broadcasts G commands, so there are N broadcast interactions for the greatly independent connected set construction, but considering the connectivity of the intermediate nodes, there will be at most 4 $N'$ more broadcast interactions, for a total of 3N+4 $N'$ The message complexity is therefore O(N). Table 1 shows a comparison of the complexity of the algorithms.

**Table 1.** Complex comparison chart

| Algorithm name | Time Complexity | Message Complexity |
|---|---|---|
| Wan [7] | O (N) | O (nlog(N)) |
| Wu [8] | O (△^3) | O (N^2) |
| DCDS [9] | O (N) | O (N) |
| DCAASN [10] | O (N) | O (N) |
| DCBNCA | O (N) | O (N) |

## 4. Simulation Experiments

In order to assess the effectiveness of the algorithm introduced in this paper, simulation experiments are set up to compare Wu, Wan, DCDS and DCAASN algorithms to show the algorithm performance. The number of network nodes is set from 50 to 200, randomly distributed in the area of 10 Km*10 Km, the communication radius is set to 0.1 Km, the maximum communication bandwidth of each node is set to 2 Mbps, the maximum degree is 5, and the initial energy is set to 5000 mA, Weighting factor $\omega_1 = \omega_2 = 0.3,\ \omega_3 = 0.4$.

As shown in Figure 5, the algorithm demonstrated above provides a greater advantage over the Wu, Wan, DCDS, and DCAASN algorithms in terms of network life cycle duration, because the energy remaining in each node is considered and the dominant node of the great independent set is strategically selected, taking into account the degree situation of the node, the bandwidth, and the remaining energy, so the network life cycle extension is effectively achieved.

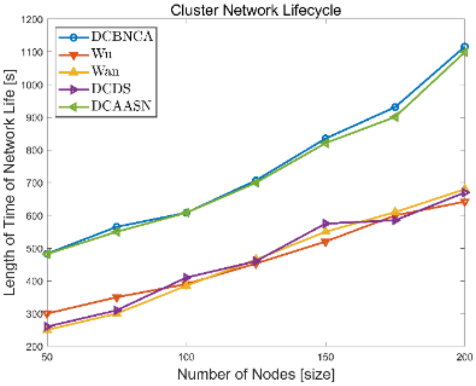

**Figure 5.** Life Cycle Comparison

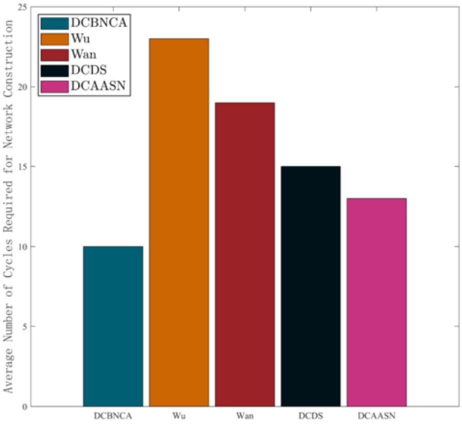

**Figure 6.** Message Cycle Comparison Chart

Figure 6 shows a comparison of the average message cycles of the five algorithms for constructing the virtual backbone network after 20 runs. As can be seen from the figure, since this paper merges the algorithm for constructing a very large independent set with the algorithm for making it connected, and puts part of the instructions for connectivity into the G instructions, eliminating the need for its additional connectivity. The algorithm proves to be more effective in accelerating the convergence speed, making the algorithm more applicable to the UAV cluster network where the topology changes relatively quickly.

## 5. Conclusion

In this paper, we apply the theory of connectivity dominating set to solve the construction problem of virtual backbone networks. Firstly, it takes into account the degree, energy, and bandwidth of network nodes and designs a composite weight function to improve the network life cycle and routing efficiency. Secondly, the construction of a very independent set is merged with the connectivity process to speed up the construction efficiency of the virtual backbone network. The experimental outcomes demonstrate that the algorithm introduced in this paper achieves significant performance improvements, making it a suitable choice for topology control in UAV cluster networks.

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