Distributed Construction of Fault-Tolerance Virtual Backbone Network for UAV Cluster Network

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Abstract. Unmanned aerial vehicle (UAV) cluster operations adopts the ad-hoc networking, and thus the network performance relates to the virtual backbone network (VBN). Because of the high-speed mobility of UAVs, the topology of UAV network changes frequently, so the VBN must have some fault-tolerant capability. And therefore a distributed fault-tolerant VBN construction algorithm named DKCDS was proposed based on the connected *k*-dominating sets. Firstly, the CDS was constructed. And then the *k*-dominating set was constructed based on the maximum independent set, thereby, the connected *k*-dominating set was finished. Theoretical analysis and simulation showed the DKCDS algorithm could obtain smaller-scaled connected *k*-dominating backbone network with smaller cost, which means the DKCDS has some application prospect in the filed of UAV cluster operations.

Keywords: UAV cluster · VBN · Distributed · Fault-tolerance

1 Introduction

UAV are paid attention to by the worldwide military due to its unique advantages in recent years. And the UAV cluster operations can expand the search range of single unmanned aerial vehicles, and improve the accuracy of reconnaissance and precision strike capability effectively [1]. Besides, single unmanned aerial vehicle failure or be shot down that will not affect the implementation of the entire collaborative operational plan [2]. Therefore, UAV cluster operations has great development prospects in the military field.

UAV cluster operations requires each node sharing the different target data with one another, so as to carry out the cluster tactical planning effectively, and improve the air combat capability [3]. Due to the limited wireless spectrum resources and the attenuation and interference of the wireless links, the bandwidth resource is the most important network resource for the unmanned aerial vehicle cluster system. And the communication interference between nodes will result in a sharp decline of the network performance due to the limited communication bandwidth [4]. However, the virtual backbone network (VBN) can simplify the routing of UAV cluster network, improve the utilization rate of network resources and reduce the difficulty of network protocol design

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effectively. Therefore, it is significant to construct VBN by using distributed algorithm [5]. The problem of virtual backbone construction is usually abstracted as the solution of the connected dominating sets (CDS) based on the graph theory. The study of the VBN construction is focus on how to reduce the VBN scale mostly [6]. However, due to the dynamics of the network topology, which makes the frequent change of the link state [7]. So some virtual backbone redundancy has an important role in improving the network fault tolerance and routing diversity for the UAVs cluster network. However, the existed algorithms based on connected *k*-dominating set for VBN are centralized almost, and the algorithm cost is high, and also have some limitations. Therefore, a distributed fault-tolerant virtual backbone construction algorithm named DKCDS was proposed based on the connected *k*-dominating sets based on the preliminary findings in this paper. And this algorithm could obtain smaller-scaled connected *k*-dominating backbone network with smaller cost, which means the DKCDS has some application prospect in the filed of UAV cluster operations.

2 Mathematical Model

Unit-disk graphs (UDG) are usually used to describe the topology information of wireless ad hoc networks. Assume that all the nodes with the same communication distance are placed in a 2-dimensional plan. If the maximum transmission range is 1, the topology can be modeled as a UDG shown in Fig. 1, from which we can see that there is an edge between any two nodes in the case that their distance is at most one.

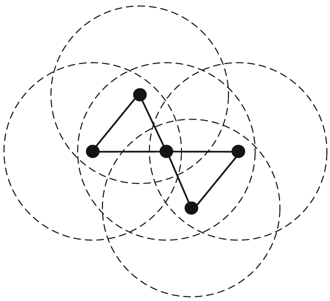

Fig. 1. UDG model.

3 DKCDS Algorithm

3.1 Related Theories

Given graph $G = (V, E)$. Among them, V is the node set and E is the edge set of graph G.

DKCDS algorithm will use the following concepts of graph theory:

***k*-dominating** assume, if any node is dominated by at least k nodes in D, D is called one k- dominating set in figure G.

DKCDS algorithm will use the following graph theory [8]:

Theorem 1. Any maximal independent set (MIS) of G is also its minimum dominating set.

Theorem 2. If B is a k-dominating set of graph G, I is a dominating set of residual subgraph G-B is a $(k + 1)$-dominating set of graph G.

3.2 Algorithm Describe

DKCDS algorithm for constructing k-dominating CDS including three steps: In CDS constructing step, DBCDS distributed algorithm is used to construct the CDS in literature [4]. In the second step the k-dominating set is constructed based on the CDS, the construction of which is compSeted by extending the maximal independent set according to Theorem 2.

The DKCDS algorithm sets the following variables for each node.

(1) Assign unique identifier (ID).
(2) Weight W.

For any node u in the graph, defines its weight as $w(u) = (r(u), ID(u))$, among which $r(u)$ represents the maximum communication distance of node u and $ID(u)$ represents its tag signal. If $w(m) > w(n)$, the node m and n must be satisfied one of the follows cases:

Case 1: $r(m) > r(n)$.
Case 2: $r(m) = r(n)$ and $ID(m) > ID(n)$.

In addition, the DKCDS algorithm sets the parameters LN for each dominating node u. The value of LN value represents the number of neighbor nodes dominating by the node u.

3.2.1 CDS Construction

Constructing a connected dominating set with the DBCDS distributed algorithm in literature [4].

3.2.2 k-Dominating Set Construction

After the construction of CDS, the maximal independent set is extended according to Theorem 2. First of all, each node is assigned a dominating neighbor list *DNList*, which is used to record the dominating neighbor nodes. In addition, *NList* represents its neighbor node set. Assuming that we can get the maximal independent set is I1 when construct CDS with the DBCDS algorithm and the corresponding connected dominating set is C, and the ith cycle get the dominating set $I_i (2 \leq i \leq k)$. The expansion process is shown in Fig. 2.

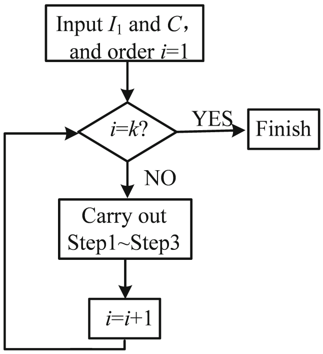

Fig. 2. Constructing k-dominating set flow.

The expending steps are as follows:

Step 1: Set $G' = G - C$
Step 2: Constructing a maximal independent set I_i for G' with the maximum independent set construction algorithm of DBCDS.
Step 3: set $C = C \cup I_i$

After the compSetion of the expansion step shown above, we can get the k-dominating set $I' = C \cup I_2 \cup \ldots \cup I_i \cup \ldots \cup I_k$, and therein I' is the k-dominating CDS set needed to be computed.

Suppose that there are 20 UAV nodes in a UAV cluster network, the nodes are distributed in a 2-dimensional plane that are 100 km × 100 km randomly, and the maximum communication distance of the nodes is 60 km.

Figure 3 shows the results of the DKCDS algorithm for constructing 2-connected k-dominating CDS. In Fig. 3, the nodes 1, 5, 8, 16, 18, 20 constitute a CDS, and the dominating set of the remaining nodes other than the CDS node are $I_2 = \{7, 12, 15\}$, and thus $CDS \cup I_2$ forms a 2-dominating set of the network.

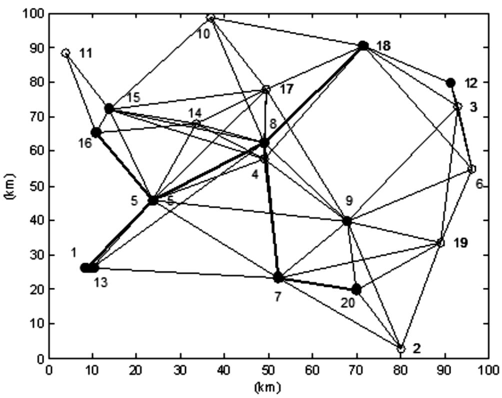

Fig. 3. An example of DKCDS for constructing 2-dominating CDS.

4 Performance Analysis

4.1 Complexity Analysis

Assuming that the nodes number of the network is n, and the maximum value of node degree is Δ.

In the first step of the DKCDS algorithm, the message complexity for constructing CDS is $O(n)$ and the time complexity is $O(n)$ with the DBCDS algorithm. In the first step of the DKCDS algorithm, the message complexity and the time complexity for constructing a maximum independent set of graphs are $O(n)$ by the literature [4]. And thus, the message complexity is $O(n)$ and the time complexity is $O(n)$ for the iterative computation ($k-1$)-dominating set for the set of assignments in the complement graph G in the worst case. And therefore, the message complexity in the worst case is $O(n)$ and the time complexity is $O(n)$ of the second stage. So both of the time complexity and the message complexity of the DKCDS algorithm in the worst case are $O(n)$.

Conclusion 1: Both the message complexity and the time complexity of DKCDS algorithm are $O(n)$.

4.2 Approximation Factor Analysis

Lemma 1: In UDG, any maximum independent set has the relationship with the minimum connected k-dominating set shown as follows:

(1) If $k < 5$, $|I| \leq \frac{5}{k}|D_k|$;
(2) If $k \geq 5$, $|I| \leq |D_k|$.

Where, $|D_k|$ represents the nodes number of $|D_k|$ that is the minimum connected k-dominating set, and $|I|$ represents the nodes number of the maximum independent set.

Suppose that *opt* represents the nodes number of the optimal k-dominating set. C represents the CDS constructed in the first step, so we can get that

$$|C| \leq \rho|D_k| = 8|D_k|, \tag{1}$$

Where, $|C|$ is the nodes number of the CDS and ρ is the approximation factor of the CDS construction problem.

In addition, the k-dominating set satisfies that $opt \geq |D_k|$. According to Lemma 1, the nodes number added by the DKCDS algorithm in the k-dominating set expansion step satisfies that

$$opt \leq \begin{cases} (8 + \frac{5}{k})|D_k| & k < 5 \\ 9|D_k| & k \geq 5 \end{cases}, \tag{2}$$

Therefore, the approximation factor of DKCDS are $8 + \frac{15}{k}$ when $k < 5$ and 9 when $k \geq 5$. And we can get Conclusion 2.

Conclusion 2: Given k, the approximation factor of DKCDS is constant.

The message complexity reflects the number of information interactions required to construct the virtual backbone network, the time complexity reflects the computational complexity of the algorithm and the approximation factor reflects the size of the virtual backbone network. Besides, the approximation factor is constant indicates that the scale is relatively smaller. Therefore, DKCDS algorithm can adapt to mobile UAV cluster network.

5 Simulation Experiment

Simulation Experiment 1: Suppose that the nodes' maximum communication distance is [100 km, 150 km]. Set $m = 1$, $k = 1$, $m = 1$, $k = 2$ and run the DKCDS algorithm 1000 times, respectively. In each simulation scenario, all the nodes are distributed in a 2-dimensional square plane with 200 km × 400 km area randomly. Figure 4 shows the relationship between the average size of VBN and the number nodes of network.

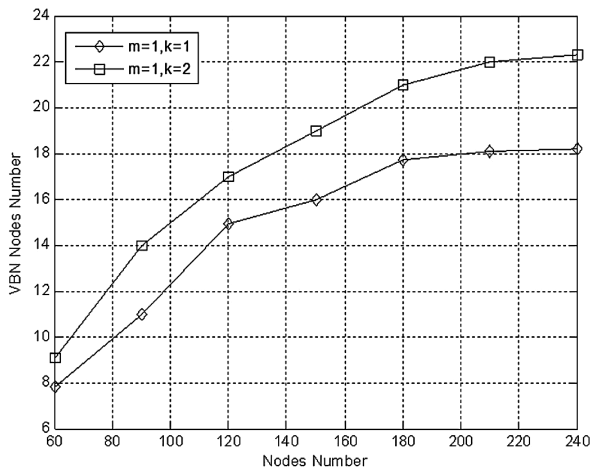

Fig. 4. Simulation result 1.

Figure 4 shows that the nodes number of CDS generated by the DBCDS algorithm increases steadily as the increases of the nodes number of the network, which indicates that any node can communicate with more nodes with the increase of the nodes number in a definite area. When the nodes number reaches or exceeds 170, certain nodes will be able to cover the entire network, so the number of CDS nodes becomes stable.

Simulation Experiment 2: Suppose that all the nodes are distributed in a 2-dimensional square plane with 200 km × 400 km area randomly, and the maximum distance of all the nodes are the same. Set $m = 1$, $k = 1$, $m = 1$, $k = 2$ and run the DKCDS algorithm

1000 times, respectively. Figure 5 describes the relationship between the average nodes number of VBN and the communication distance of the nodes.

Figure 5 shows that these two types of VBN nodes are less and less with increases of the node maximum communication distance, which indicates that fewer nodes can cover the whole network with the increase of the nodes coverage. When the maximum communication distance is 0.75 times or more of the area length, the node coverage almost reaches the area boundary. At least one node can communicate with any other node at the moment. So the nodes number of the connected 1-dominating VBN tends to be the constant 1, and the nodes number of the connected 2-dominating VBN tends to 2 because each node is connected to at least two dominating nodes.

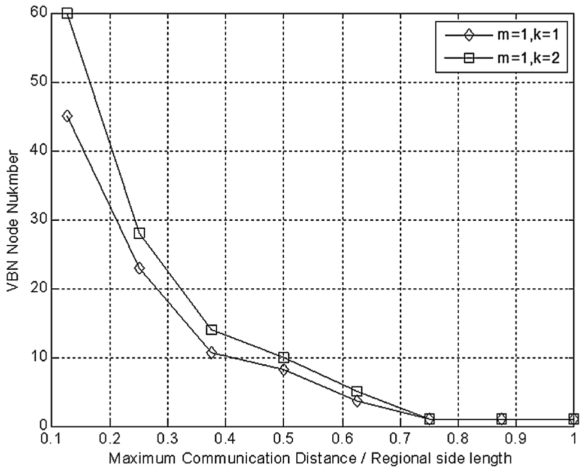

Fig. 5. Simulation result 2.

In addition, the existing *m*-connected *k*-dominating VBN construction algorithms are mostly for the determined values of *m* or *k*. So the simulation experiment is not compared with other algorithms.

6 Conclusion

Considering the high speed mobility of UAV cluster nodes and the limitation of wireless spectrum resources, a distributed fault-tolerant virtual backbone network based on connected *k*-domination is proposed to improve the cooperative combat capability. A CDS was constructed based on the previous research, and then k-domination set was constructed. Theoretical analysis showed that the message and time cost of the DKCDS algorithm are O(*n*) and the approximation factor is constant. That indicated the DKCDS algorithm can get the smaller-scaled VBN with lower communication cost. Simulation results verified the effectiveness of the DKCDS algorithm. As the *m*-connected virtual backbone network construction cost is very high, the future study will focus on constructing the *m*-connected *k*-dominated VBN with lower overhead.

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