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Node Locations-based Ad-Hoc Topology Analysis Using Minimum Connected Dominating Set

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Abstract. *In the battlefield environment, sometimes only the location information of the battlefield network nodes can be obtained, but it is difficult to obtain the communication relationship information between the nodes. In this case, it becomes very difficult to identify the topology. However, from the perspective of network coverage design and topology control, this is similar to a distributed topology control algorithm based on node location information. This paper presents a scheme based on minimum connected dominating set to solve the problem of Ad hoc access network topology analysis, it can finally output key nodes and key links. The core idea is to find the smallest number of dominators among all network nodes as key nodes. The shortest path between the two dominators is the critical link.Experimental results demonstrate the effectiveness of the proposed scheme.*
Keywords: Mobile Ad hoc network, Topology analysis, Minimum connected dominating set, Key nodes, Key links.

1. **Introduction.** MANET (Mobile Ad-hoc Network)[1] refers to a mobile ad-hoc network composed of several mobile nodes without fixed infrastructure support. MANET is independent of any static infrastructure, the networking is flexible and fast, the status of each node in the network is equal, and the communication is carried out through the wireless interface. MANET is mainly used in situations that require rapid establishment of mobile and flexible communication systems, such as emergency rescue, disaster relief, rescue, exploration, military operations, emergency missions, and temporary major events. If you want to attack the enemy's network, you must first obtain the structure of the enemy's network and understand its network characteristics. However, it is impossible for the enemy's network to actively tell us its topology. We can only infer its topology by detecting and intercepting the enemy's communication signals. The network topology inference method [2,3] mainly solves the problem of how to infer network structure information such as the enemy's network scale, node composition, and communication relationship based on the reconnaissance and intercepted enemy battlefield wireless communication network signal information under non-cooperative conditions.

The network key node/link analysis [4,5] mainly solves the problem of how to analyze the key nodes/links that have the greatest impact on the enemy's battlefield wireless network connectivity and other important performances under the premise that the network topology is known. The main idea is to analyze the centrality of network nodes/links on the basis of network topology inference, and then determine the key nodes/links of the network.

According to the different known conditions, the identification of key points of the battlefield wireless network includes two categories: unknown topology[6] and known topology[7]. Our paper studies the situation where the topology is unknown. The main idea is to infer the key nodes and key links of the enemy's network based on the results of wireless signal reconnaissance. It is based on the radio signals of the enemy's network obtained by reconnaissance, through signal analysis, traffic analysis and bit stream analysis, and with the help of data mining methods, it can infer the key nodes and key links of the enemy's battlefield wireless network.

When the wireless link is encrypted, the data obtained by detection includes node position, signal connection relationship, flow, and bit stream; when the link layer address can be obtained, the data obtained by detection also includes data frame address information. When there are a large number of user terminals on the battlefield wireless network, access networks are often formed through classification, grouping, and subnetting (ad hoc networks are often used). The access networks are interconnected by backbone links to form a backbone network. The topological structure of the access network [8] is relatively simple, but changes rapidly, and the topological structure of the backbone network [9] is relatively complex (Mesh network is mostly used), but the change is slow. This subject mainly focuses on the identification of key nodes and key links in the access network. For the backbone network, because each node and link is very important, it is necessary to study the inference method of the entire topology.

There are many ways to evaluate the importance of nodes [10-16] in the network, but their essence is derived from graph theory and graph-based data mining, which corresponds to the most vital node problem and most vital edge problem in graph theory. The research on the importance of nodes in complex networks first began in the field of social network analysis [13], and is still the focus of academic research. With the continuous deepening of research on complex networks, similar issues have been raised independently in the fields of system science research and information search. So far, mining key nodes and key edges in the network has become a basic problem in the field of network science.

In the battlefield environment, sometimes only the location information of the battlefield network nodes can be obtained, but it is difficult to obtain the communication relationship information between the nodes. In this case, it becomes very difficult to identify the topology. However, from the perspective of network coverage design and topology control, this is similar to a distributed topology control algorithm based on node location information. The solution considered in this paper is to find an optimal network coverage structure, which needs to meet three conditions: (1) The number of partitions in the coverage is as small as possible; (2) The overlap of the partitions is as small as possible; (3) Try to balance the number of nodes in each partition. Under this condition, combined with Ad hoc network layering and clustering ideas, the problem of finding the optimal coverage structure can be transformed into the problem of finding the smallest connected dominating set of graphs. Therefore, the research team intends to adopt a method based on the smallest connected dominating set to solve the problem. The key node and key link analysis problem of Ad hoc access network. The core idea is to find the smallest number of dominating nodes in all network nodes as key nodes, and the connection between the two dominating sets is the key link. The remainder of the paper is organized as follows.

Section 2 gives the proposed scheme. Section 3 gives the experimental results. Section 4 concludes the whole paper.

2. **Proposed Scheme.** Because our scheme is based on the minimum connected dominating set, we first introduce some concepts related to the minimum connected dominating set. The mathematical definition of the minimum connected dominating set is as follows: Let the graph $G = (V, E)$ be a simple undirected graph, V is the set of nodes, and E is the set of edges. Assuming that any two points in the node subset I of V are not adjacent, call I the independent set of G, and the nodes in I are called independent points. Let I be an independent set, and if any other node is added to I so that the new I is no longer an independent set, then I is called a maximal independent set. Suppose graph $G = (V, E)$, C is a node subset of V, if any node u in the set $V - C$ has an edge with a node v in the set C, then v is called the dominator, and call C a dominating set of G. If C is the dominating set of G, but any proper subset of C is not the dominating set of G, then C is called the minimal dominating set. The dominating set with the smallest number of nodes is called the smallest dominating set. If the subgraph derived from the dominating set C is a connected graph, we call C the connected dominating set. The connected dominating set with the smallest number of points is called the smallest connected dominating set. The independent set and the dominating set have a very close relationship. There is a theorem in graph theory that shows that each maximal independent set of the graph G must be a minimal dominating set. Therefore, in all the algorithms for solving the minimal dominating set of the graph G, there is a method of finding connected dominating sets by constructing independent sets. Solving the minimum connected dominating set in any graph is an NP complete problem, so heuristic algorithms are often used in practical applications to find its approximate solution. In most wireless applications, a distributed method is often used to solve the problem. By using local node information, a distributed method is used to construct a connected dominating set. After obtaining the minimum connected dominating set of the network, all the dominators are key nodes, and the connection between the two connected dominating sets is the key link.

The following subsections give the specific scheme of the Ad hoc network based on the minimum connected dominating set topology used in this subtopic, as shown in Fig. 1. This scheme uses a Minimum Connected Dominating Set (MCDS) construction algorithm based on a distributed mechanism. The algorithm is based on the construction of the Maximal Independent Set (MIS) (its node is called the dominator), and finds the unique shortest path to connect a pair of dominating nodes within three hops of each other, and the algorithm has complete locality. Each node only needs to know the information of neighbors around one hop. The nodes on this shortest path are called connectors. All dominators and connectors constitute MCDS. The specific description is as follows:

2.1. **Known conditions.** It is assumed that the position coordinates of N nodes of the Ad hoc network have been obtained by means of investigation. Other assumptions: All nodes use omnidirectional antennas, and their wireless transmission radius is r; if the geometric distance between two nodes is less than the wireless transmission radius, it is considered that there is an edge between the two nodes. In addition, it is assumed that each node has a unique node ID and knows the IDs of all its one-hop neighboring nodes. The ID of the neighbor node can be obtained from the message sent by each neighboring node. In other words, the known condition is N nodes' numbers and positions, and the connection relationship between nodes is described by the Unit-Disk Graph model. A UDG diagram is shown in Fig. 2. Some basic definitions are given below to facilitate the understanding of the algorithm. Definition 1: Domination set (DS). A subset S of the set

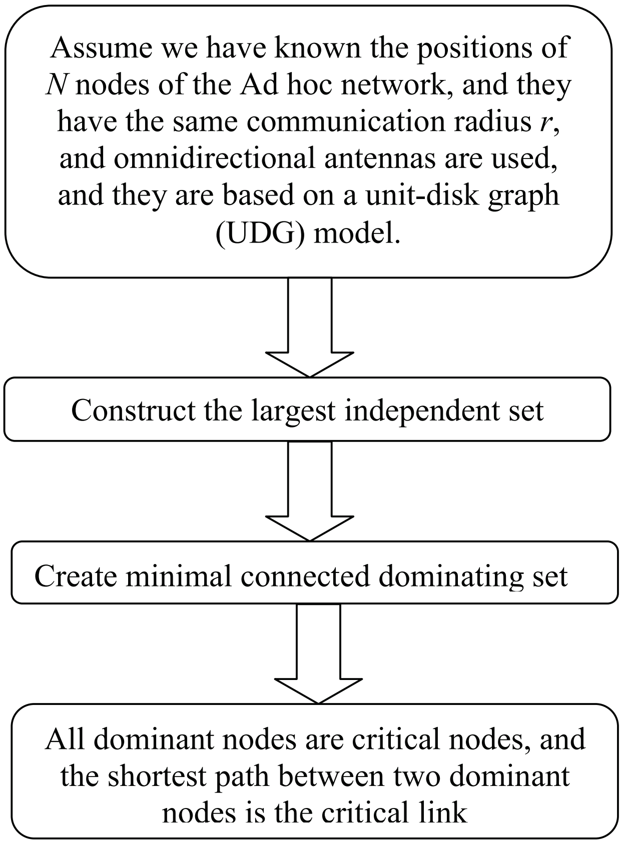


FIGURE 1. Topology analysis scheme based on minimum connected dominating set

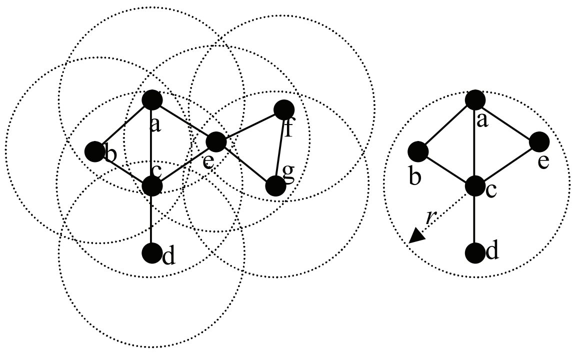


FIGURE 2. The meaning of the UDG model (the figure on the right represents the neighbor node of node c)

V is a dominating set (DS) and needs to meet the following conditions: each node u in V either belongs to S or is adjacent to a certain node v in S. The nodes in S are called dominating nodes, and the nodes that do not belong to S are called dominated nodes.

Definition 2: Connected Dominating Set (CDS). When C is a dominating set, and C itself constitutes a connected graph, then C is called the connected dominating set, CDS. The nodes in the connected dominating set C can use the nodes in the $V - C$ to

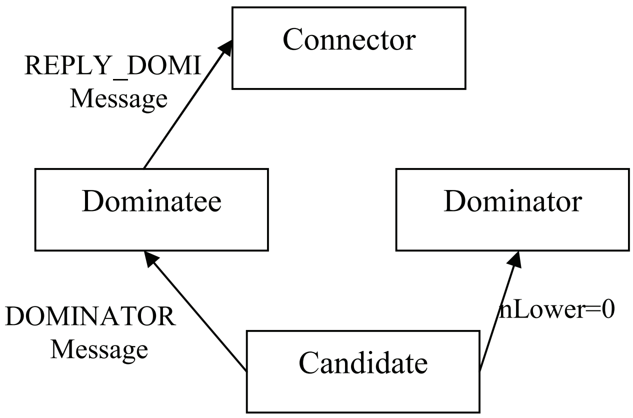


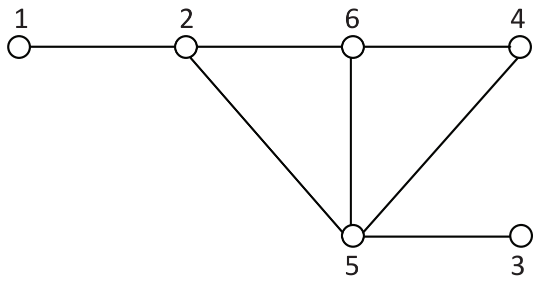
FIGURE 3. The state transition diagram of the algorithm

communicate with each other. The dominating set with the least number is called the minimum dominating set, denoted by MDS. The connected dominating set with the least number of nodes is called the minimum connected dominating set, which is represented by MCDS.

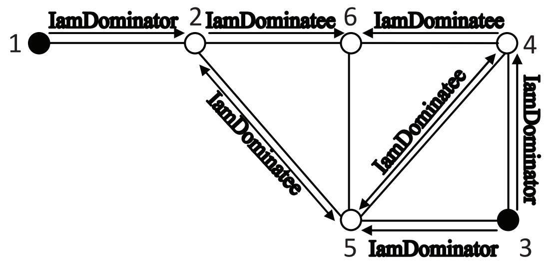
Definition 3: Independent Set (IS). The condition for a subset I of the node set V of graph G to be an independent set is that there is no common edge between any two nodes in I. MIS is the independent set I with the largest number of nodes in the node set V.

2.2. **Establish the largest independent set of MIS.** In this solution, each node in the network is in one of the following four states, namely candidate, dominator, dominatee, and connector. The initial state of each node is a candidate, and then it enters the dominator state and the dominatee state. The state of the connector can only be transformed from the state of the dominatee. Fig. 3 shows the state transition diagram of the entire program. In the MIS algorithm, each node is given a variable nLower, which is initialized to the number of one-hop neighboring nodes smaller than the node's own ID. The MIS algorithm runs on each candidate until the state of all candidates has changed. The process is as follows: If the nLower of a candidate is 0, change its state to the dominator, and then broadcast a DOMINATOR message. When a candidate receives the DOMINATOR message, it changes its state to the dominatee, and then broadcasts a DOMINATEE message. When a candidate receives a DOMINATEE message, if the node ID that sent the message is less than its own node ID, its nLower will be reduced by 1, if the value of nLower becomes 0 at this time, its status will be changed to dominator, and then broadcast DOMINATOR messages. When all candidates have changed their states, the algorithm stops. The pseudo code of the algorithm is as follows (the actual example is shown in Fig.4):

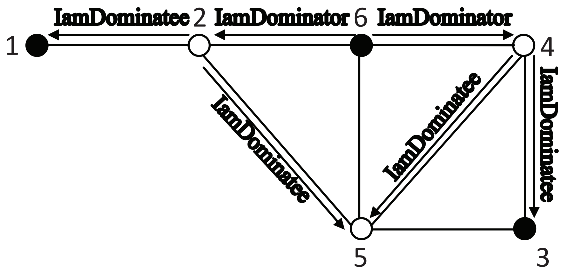
```
Start
while node. status= =candidate
if node. nLower= =0 then
node. status=dominator
broadcastMessage(DOMINATOR)
endif
if received DOMINATOR then
```



(a) Topological diagram (initial state)



(b) Nodes 1 and 3 where nLower is 0 become dominators



(c) After nLower is reduced to 0, node 6 eventually becomes the dominator

FIGURE 4. MIS algorithm example (black is the dominator, gray is the dominatee, and white is the candidate)

```
node. status=dominatee
broadcastMessage(DOMINATEE)
endif
if received DOMINATEE then
if(node. ID¿sourcenode.ID) then
node. nLower- -
endif
if(node. nLower = =0)then
node. status=dominator
broadcastMessage(DOMINATOR)
endif
endif
endwhile
End
```

2.3. **Create the minimum connected dominating set(MCDS).** At this stage, each dominator broadcasts a REQUEST_DOMI message to find other dominators within three hops. This message is broadcast at most three times before it reaches another dominator. When a dominated node receives a REQUEST_DOMI message from another dominating node for the first time, the dominated node adds its node ID to the node list in this message, and then broadcasts the message. In this way, when a REQUEST_DOMI message reaches another dominating node, these node IDs constitute the shortest path from the dominating node that sent the message to the dominating node that received the message. When a dominating node receives a REQUEST_DOMI message from another dominating

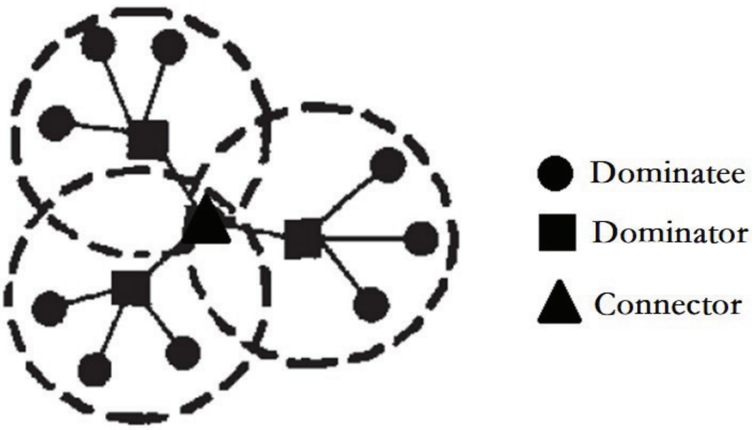


FIGURE 5. The diagram example of MCDS

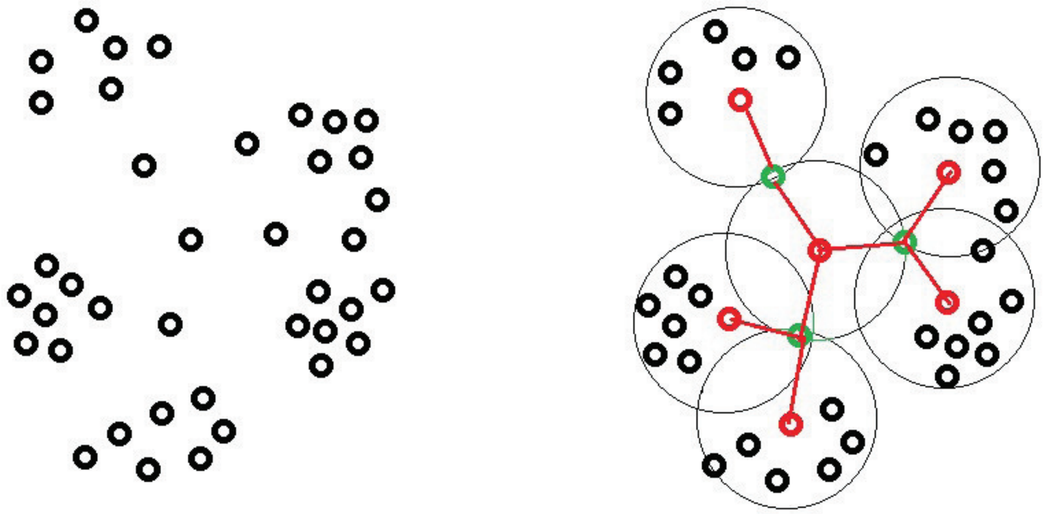
node for the first time, it generates a REPLY_DOMI message. This message contains the node path that the message has passed through, and then sends this REPLY_DOMI message to the next node in the path. The path message contained in the REPLY_DOMI is copied from the node list contained in the received REQUEST_DOMI message, but the order is reversed. When the ID of a dominated node is in the path included in the REPLY_DOMI message, after receiving the REPLY_DOMI message, it changes its state to a connected node and forwards the message to the next hop node indicated in the path. If two dominating nodes within three hops send out REQUEST_DOMI messages at the same time, only the dominating node with the smaller node ID will send the corresponding REPLY_DOMI message after receiving the REQUEST_DOMI message from the other party to select the connected node, and then Create the shortest path between two nodes. This avoids the creation of multiple paths between dominators within three hops. A simple MCDS chart example is shown in Fig. 5.

2.4. **Obtain key nodes and key links.** According to the created minimum connected dominating set MCDS, all dominating nodes and connecting nodes are taken out to form a key node set, and the shortest path between two dominating nodes is the critical link. An example of the identification of key nodes and key links based on the minimum connected dominating set is shown in Fig. 6.

3. Experimental Results and Discussions.

3.1. **Programming Environment.** At present, the simulation algorithm uses the Microsoft Visual Studio 2010 platform as the development environment and C++ as the main development language, and is developed and deployed on the Windows platform. Since the core algorithm is developed in C++ language, it has good portability, and the algorithm can be transplanted into OPNET, OMNeT++ and other simulation platforms in the future.

3.2. **Applicable scenarios.** The current scenario where the algorithm is applicable is to detect the positions of N nodes in the Ad hoc network that have been obtained, the algorithm identifies the key nodes and connection nodes among the N nodes, and obtains the key links between the key nodes. Among them, the MIS algorithm obtains the key nodes through the message communication of N nodes, and then the MCDS algorithm infers the connection nodes and obtains the key path through the necessary communication between the key nodes. By integrating the algorithm into a simulation



(a) Node locations obtained by reconnaissance (b) Key nodes and critical links

Figure 6. An example of inferring key nodes and key links based on the idea of minimum connected dominating set(circles indicate communication ranges, red and green nodes are key nodes, red indicates dominating nodes, green indicates connecting nodes, and red edges are critical links)

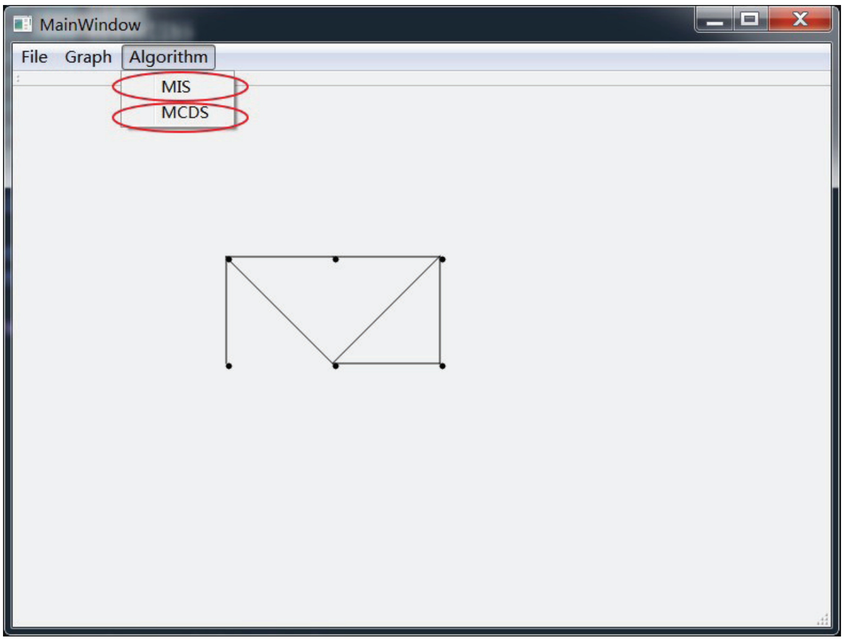


Figure 7. The main interface of the simulation software

platform such as OPNET, it can make it suitable for the discovery of key nodes and critical paths of WIN-T network.

The simulation software interface is shown in Fig. 7. The current main functions include random simulation point generation algorithm, MIS algorithm and MCDS algorithm.

Software simulation steps:

1. Randomly generate N nodes to simulate the detected N nodes (Fig. 8).

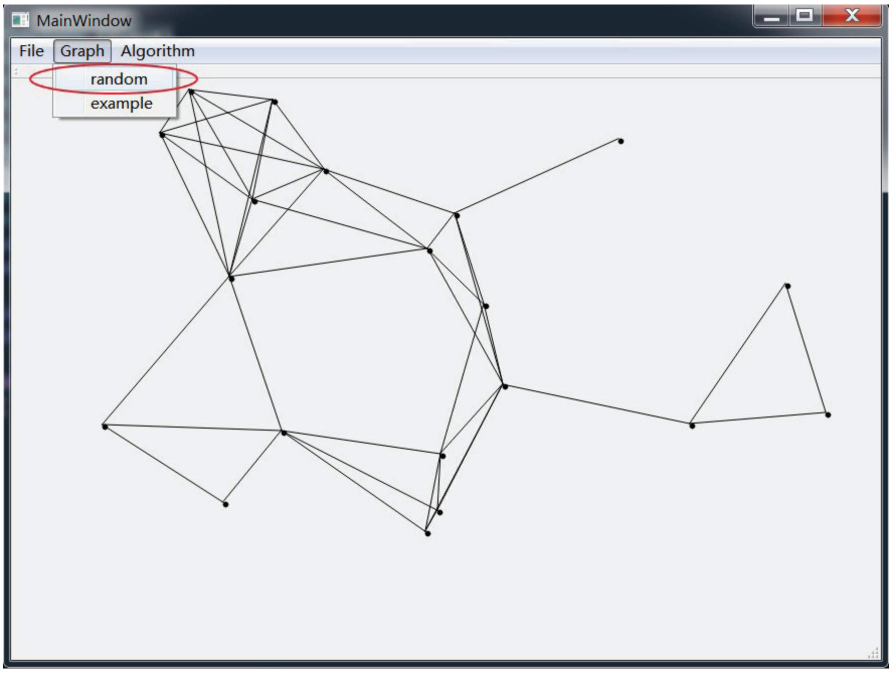


FIGURE 8. Generate random simulation nodes

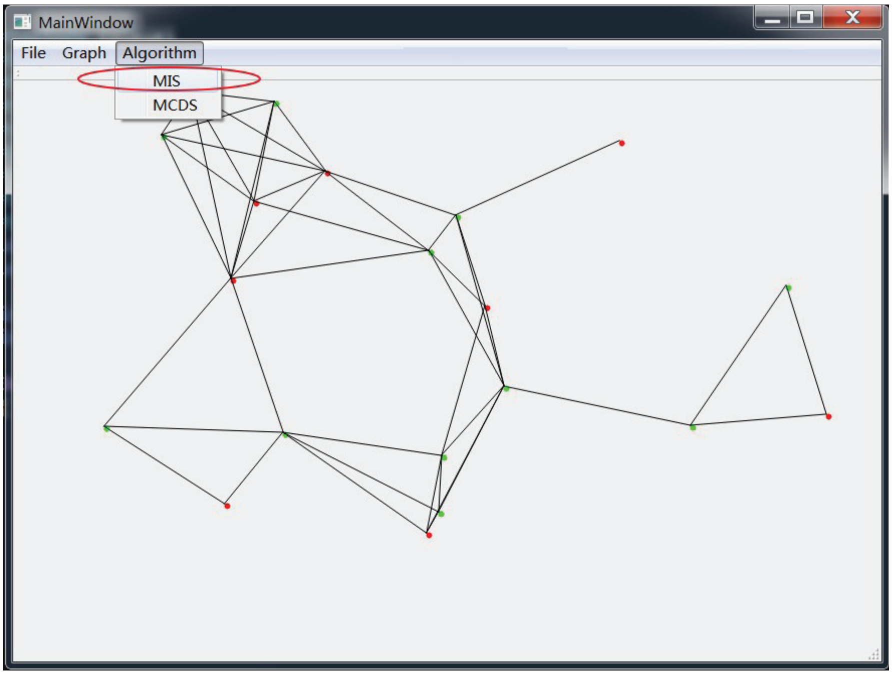


FIGURE 9. Finding key nodes through MIS algorithm

2. Run the MIS algorithm to find the key nodes and non-key nodes (Fig. 9).
3. Run MCDS to find the critical path between the key nodes (Fig. 10).

In order to evaluate the effectiveness of the proposed scheme, we test the average detection accuracy using five real test networks, one example is shown in Fig. 11. We compare our scheme with the distributed topology control algorithm based on minimum spanning tree in terms of the average key node recognition accuracy, the average key link

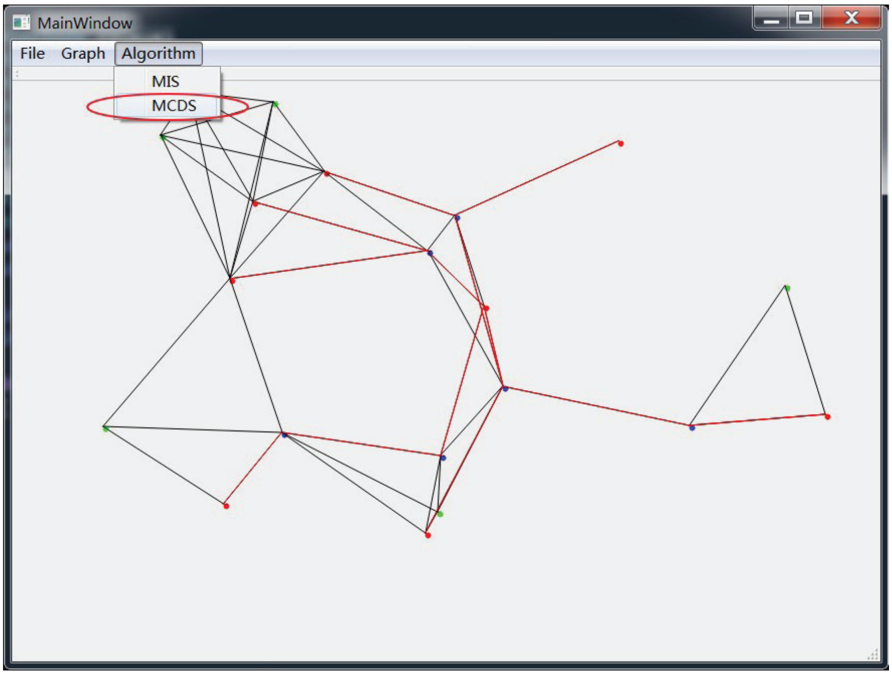


FIGURE 10. Find the critical path through the MCDS algorithm

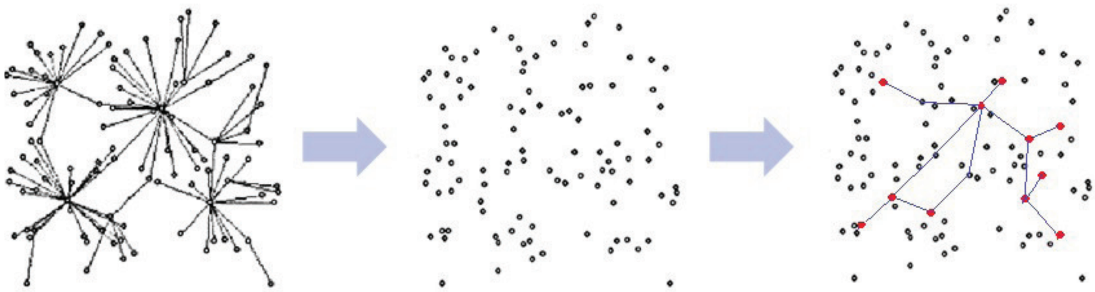


FIGURE 11. An example of inferring key nodes and key links based on the idea of minimum connected dominating set

TABLE 1. Comparisons of our scheme with the MST scheme in terms of average accuracy and average time complexity

Method	MST	Our
Average key node recognition accuracy	70.2%	87.8%
Average key link recognition accuracy	75.1%	88.6%
Average time complexity	1.53	1.0

recognition accuracy, and the average time complexity. The basic idea of the minimum spanning tree (MST) based scheme is that each node in the network only collects the neighboring node information within its maximum transmission range to construct a local minimum spanning tree to obtain the local local topology; then, each node sets its transmission power to reach its nearest hop neighbor's minimum required power. The entire network topology consists of the local topology of all nodes in the network. The comparison result is shown in Table 1.

3.3. **Analysis of results.** From the current simulation results, the topology inference method based on the minimum connected dominating set can well infer the key nodes and critical paths of the network. However, since the strict MCDS algorithm is NP-complete, the improved MCDS algorithm will exponentially The time complexity of is reduced to polynomial time, the time complexity is $O(N)$, and the message complexity is $O(NlogN)$. In order to be able to apply the algorithm to disconnected networks, the algorithm further adds a breadth-first search to ensure non-main The connected branch of the can also get the corresponding key link, which increases the time complexity of the breadth first search $O(|V|+|E|)$, so the total algorithm complexity is $O(|V|+|E|)$, The message complexity is $O(NlogN)$, which has reached the efficiency of the best MCDS algorithm at present.

4. **Conclusion.** This paper presents a scheme based on minimum connected dominating set to solve the problem of Ad hoc access network topology analysis, it can finally output key nodes and key links. The core idea is to find the smallest number of dominators among all network nodes as key nodes. The shortest path between the two dominators is the critical link.Experimental results demonstrate the effectiveness of the proposed scheme. In the future, we will improve our scheme. The current transformation environment is carried out under Visual Studio 2010. In order to simulate the real network scene as much as possible, the next step will be to use OPNET as the main programming environment to improve the authenticity of the simulation. Judging from the current data, this is not difficult to achieve, because OPNET itself is also written in C++ language, which provides a rich API interface, so it can well transplant the algorithm to the OPNET platform to simulate in WIN- In the T network environment, this algorithm is used to identify key nodes and critical paths, and then infer the topology. The algorithm is currently only suitable for the inference of key nodes and critical paths of Ad hoc networks, and then infers the topology. As long as the network topology has no or less impact on the virtual backbone network composed of connected dominating sets, the topology can be inferred by recalculation. In view of the significant changes in the Ad hoc topology that affect the virtual backbone network of the connected dominating set, it is necessary to make appropriate improvements to the algorithm to adapt to this network. The algorithm currently considers the critical path inference of key nodes within three hops, and the number of communication hops between nodes of the Mesh network is greater than three hops. Further, it is necessary to consider the case of hops greater than three to make the algorithm suitable for Mesh. The internet. The algorithm currently infers the network topology at the same level, while the WIN-T network is multi-level across sea, land and air. Currently, the algorithm can only infer the topology of each level of the network, but cannot solve the problem of inferring the critical path of network nodes at different levels. The next step is to consider improving the algorithm to solve the problem of topology inference between cross-layer networks.

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