Hindawi
Journal of Control Science and Engineering
Volume 2019, Article ID 5860461, 8 pages
https://doi.org/10.1155/2019/5860461

Research Article

Hierarchical Evolution Model of Command and Control Network Based on Hypernetwork

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Received 14 December 2018; Accepted 8 July 2019; Published 16 July 2019

Academic Editor: Paolo Mercorelli

According to the hierarchical structure of command and control network and the characteristics of hypernetwork such as heterogeneous nodes and multiple links, a hierarchical evolution model of command and control network based on hypernetwork is established. Considering the nonuniqueness of the number and frequency of new joining nodes in different layers, a different number of new joining nodes are set in different layers, and the frequency of new joining nodes in each layer is set. A $K(M_n + 1)$ strategy of hierarchical joining of nodes is proposed. The theoretical derivation and simulation prove that the network model has scale-free characteristics. The simulation analysis of different measurement indicators shows that the hierarchical command and control hypernetwork has higher command efficiency, better connectivity between nodes, and stronger reliability of organizational structure.

1. Introduction

With the wide application of communication and network technology in modern local warfare, information warfare has gradually become a new mode of warfare on the battlefield. With the unprecedented increase of battlefield mobility, the increase of activity space, and the complexity of command and coordination relations, higher requirements have been put forward for the construction of command and control network [1]. Command and control network has the characteristics of heterogeneous nodes, multiple links, and time-varying topology, which makes it difficult for the traditional network model based on classical graph theory to accurately describe the structure and functional characteristics of command and control network. As a new method to study complex systems and complex problems, hypernetwork has the characteristics of network nesting, multitier structure, multidimensional information, multiple attributes, etc. It is widely used to solve practical problems. At present, it has been widely concerned in the research of command and control network model.

In recent years, the research of hypernetwork mainly focuses on the construction and characteristics of hypernetwork model. Liu et al. [2] constructed a knowledge propagation model based on hypernetwork and proposed a knowledge generation and knowledge diffusion model according to the characteristics of knowledge propagation. Zhang et al. [3] established a three-uniform hypernetwork model based on user background knowledge, object and label double priority connection mechanism. Pei et al. [4] studied the uniform dynamic network evolution model based on a kind of triangle structure. Wang et al. [5] proposed a (m+1) type uniform hypernetwork dynamic evolution model based on hyperedge growth and hyperdegree priority connection mechanism. Hu et al. [6] proposed a (1+m) type uniform hypernetwork model, which added one node at a time and formed a hyperedge with m old nodes in the network. The research on combat network model mainly focuses on principle analysis, model construction, algorithm design, and so on. For example, according to the needs of joint operations, the U.S. Army had put forward new operational concepts such as air-sea integrated warfare and cyber-electric space warfare, established operational command and control theory system such as power edge and agility advantage, and carried out the research of system integration, network reconfiguration, dynamic control and deep collaboration, etc., relying on research cooperation, information sharing, and credible experimental platform (ELICIT) [7]. Wang et al. [8] synthetically considered the heterogeneity of command and control network entities and network structure relations and established a command and control network model based on multiattribute weighting. Wang et al. [9] established a command and control hypernetwork model, proposed a network survivability measure based on combat link, and analyzed the survivability of command and control network. Liu et al. [10] established a three-layer hypernetwork evolution model based on small-world model and scale-free model. According to the characteristics of battlefield information network, such as heterogeneous nodes, complex connections, and dynamic self-adapting, Si et al. [11] proposed the construction method of multidimensional dynamic information network model of command and control system and the construction method of effectiveness evaluation model based on hypernetwork. Yang et al. [12] put forward the concept of system-based operational information flow hypernetwork and constructed a hierarchical network structure and an equilibrium model of operational information flow hypernetwork. Ginestra et al. [13] studied the network in the network, i.e., the hierarchical hypernetwork. The robustness of the whole network was studied by the change of a node in a layer of network. Guo et al. [14] constructed a unified evolution model of hypernetwork and complex network and studied the evolution mechanism and topological properties of scale-free characteristics of hypernetwork. The model is analyzed by Poisson process theory and continuation method, and the analytic expression of the steady-state average over-degree distribution of the network is obtained. Hu et al. [15], based on the cooperation mode of the authors of scientific research papers, constructed the evolution model of scientific research cooperation hypernetwork by using hypergraph theory and analyzed the evolution of the authors' published papers by using mean field theory. It is found that the author's overdistribution conforms to the power law distribution. Although the network model can well represent the network relationship of scientists' cooperation, the evolution of the network model has the problem of singularity, which makes it difficult to integrate with the network in the real world.

Combining the advantages and disadvantages of the abovementioned modeling methods, in order to build a network which not only conforms to the actual background of command and control network, but also has the flexibility of modeling, a hierarchical evolution model of command and control network based on hypernetwork is established. A different number of new nodes are set at different layers, and the frequency of new nodes is set at each layer. In order to build a command and control hypernetwork model adapted to the flexible and changeable characteristics of battlefield, the $K(M_n + 1)$ strategy of layered nodes is added.

2. Command and Control Hierarchical Hypernetwork Model

With the development of network technology, command and control network presents the characteristics of increasing number of nodes, diverse connection forms, and more complex structure. A command and control network includes three types of nodes: sensing, command and control, and fire strike. The relationship between different types of nodes and the relationship between multiple nodes in the network are difficult to express by common graph. In order to solve the above problems, three kinds of nodes are abstracted as the nodes of hypernetwork, and the cooperative relationship between nodes is abstracted as the hyperedge of hypernetwork; that is, the edge of the graph contains several nodes, which is hypergraph. The edges of a hypergraph can contain any number of nodes to represent the relationship between multiple nodes. Therefore, the command and control hypernetwork model based on hypergraph can well describe and represent the interaction and influence between nodes.

2.1. Node Abstraction of Command and Control Hypernetwork. There are three basic activities in the combat process: sensing of battlefield situation, formation of decision-making instructions, and implementation of firepower strike [16]. Considering the main functions of combat unit in the combat process, it is divided into three types of nodes: sensing node, command node, and firepower node. Three kinds of nodes are abstracted by using hypernetwork theory. The node i in the network is represented as follows:

$$V(i) = < ID\_Num, Attr, Cap > \tag{1}$$

Among them, ID_Num is the sequence identification of the combat nodes in the whole command and control network; it has uniqueness. $Attr$ presents the function set of the nodes, which is a vector. When a node has the function, the corresponding position of the vector is 1; otherwise the value is 0; Cap presents the performance set of the nodes, which is also represented by a vector. In order to unify the expression, the performance metrics are normalized. If the nodes don't have the performance, the value is set to 0, and the maximum value is 1, the larger the value, the stronger the performance.

For example, $Attr = [\mathrm{A}_1(\mathrm{C}), \mathrm{A}_2(\mathrm{C}) \cdots \mathrm{A}_m(\mathrm{C})]$ represents the operational function vector of a command node. $Cap = [\mathrm{C}_1(\mathrm{C}), \mathrm{C}_2(\mathrm{C}) \cdots \mathrm{C}_n(\mathrm{C})]$ represents the operational performance vector of a command node.

2.2. Link Abstraction of Command and Control Hypernetwork. Different battle units in command and control network need to achieve different types of information interaction processing through physical connections to meet the operational requirements of cooperative operations [10], which can be abstracted as links in the network. Information interaction among three kinds of nodes in command and control network will form multiple links. All links in the network are represented by hyperedge sets, and the formula is

$$E = \{E_1, E_2, E_3 \cdots E_{\mathrm{m}}\} \tag{2}$$

An element in a hyperedge set is expressed as

$$E_i = \{V(1), V(2), V(3) \cdots V(n)\} \quad (3)$$

Among them, E represents the set of all hyperedges in a hypernetwork, and E_i represents the set of nodes contained in a hyperedge, all of which are connected by the hyperedge.

2.3. Command and Control Hierarchical Hypernetwork Model. The command nodes often need to receive information from multiple sensing nodes. Several sensing nodes are connected with a command node by a hyperedge to represent the transmission link of information. There is information exchange and sharing between command nodes, and several command nodes are connected by a hyperedge to represent the information exchange chain between command nodes. The command node should command multiple fire nodes to carry out fire attack on combat targets. One command node and multiple fire nodes are connected by a hyperedge to indicate the downlink of fire attack command. The interaction between various types of nodes is shown in Figure 1.

The command and control network model based on hypernetwork is expressed by a formula: $G_{C^2N} = (G_{I-C}, G_{C-C}, G_{C-F})$; the expansion of the formula is expressed by a matrix:

$$G_{C^2N} = \begin{array}{c c} & \begin{array}{ccc} I & C & F \end{array} \\ \begin{array}{c} I \\ C \\ F \end{array} & \begin{bmatrix} 0 & G_{I-C} & 0 \\ G_{I-C} & G_{C-C} & G_{C-F} \\ 0 & G_{C-F} & 0 \end{bmatrix} \end{array} \quad (4)$$

Among them, I represents a set of sensing nodes, C represents a set of C2 nodes, and F represents a set of fire strike nodes. G_{I-C} represents the subnetwork formed by the interweaving of the sensing node and the command node, G_{C-C} represents the subnetwork formed by the interweaving of all kinds of command nodes at all levels, and G_{C-F} represents the subnetwork formed by the interweaving of the command node and the fire node.

3. Hierarchical Evolution Model of Command and Control Network Based on Hypernetwork

3.1. Hierarchical Evolution Model of Command and Control Network. In the existing reference [14, 15], when studying hypernetwork modeling, each of the additional n nodes establishes a hyperedge with only one existing node. This modeling method is not suitable for command and control network with hierarchical structure. It is obvious that the unified evolutionary modeling method can't express the hierarchical characteristics of command and control network.

Combining the hierarchical characteristics of command and control network and the multilayer structure characteristics of hypernetwork, a $K(M_n + 1)$ hierarchical modeling method is proposed. Considering the nonuniqueness of the number and frequency of new joined nodes in different

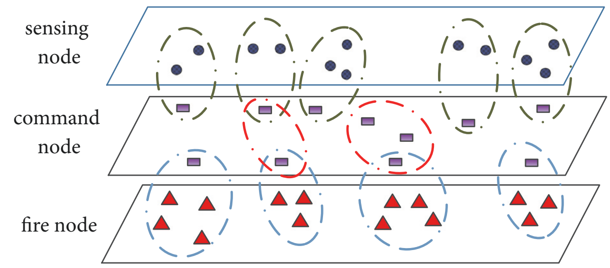


Figure 1: Command and control hypernetwork model.

layers, it shows that the values in an array M_n and an array C_n are not unique.

Among them, K represents the total number of layers of command and control network to be constructed, M_n represents the number of new nodes added at the n layer, and C_n represents the frequency of new nodes added at the n layer.

The construction process of hierarchical evolution model of command and control hypernetwork is as follows.

(1) Initialization: a hyperedge connects M_0 nodes.

(2) Network nodes increase: at the t_n time, the n level, and $1 \leq n \leq K$, from the existing nodes of network, a node is selected according to the probability $P(i)$, and the node is connected with the newly added M_0 nodes by a hyperedge.

The connection probability $P(i)$ of each node i is equal to the ratio of the hyperdegree $d_H(i)$ of the node i to the sum of the hyperdegree of existing nodes in the hypernetwork. The formula is as follows:

$$P(i) = \frac{d_H(i)}{\sum_j d_H(j)} \quad (5)$$

(3) Hierarchical transformation: When the number of new nodes in layer n is increased C_n times, the model is built in layer $(n+1)$. The number of nodes in layer $(n+1)$ is changed to $M_{(n+1)}$, and the number of nodes in layer $(n+1)$ is changed to $C_{(n+1)}$ times.

According to the above evolution rules, the hierarchical evolution process of command and control hypernetwork is shown in Figure 2.

Each layer evolves from the existing nodes and chooses one node to connect according to the probability according to the degree. The graph initialization consists of three nodes and a hyperedge. The process of hierarchical evolution is as follows: the first layer increases the number of nodes $M_1 = 3$ every time, increases $C_1 = 2$ times; the second layer increases the number of nodes $M_2 = 2$ every time, increases $C_2 = 3$ times, and so on.

3.2. Theoretical Analysis of Evolutionary Algorithms. The existing reference [17] shows that the degree of nodes in command and control network conforms to power law distribution and has scale-free characteristics. In order to verify that the $K(M_n + 1)$ hierarchical command and control hypernetwork model proposed in this paper conforms to power law distribution, theoretical analysis will be carried out in this section.

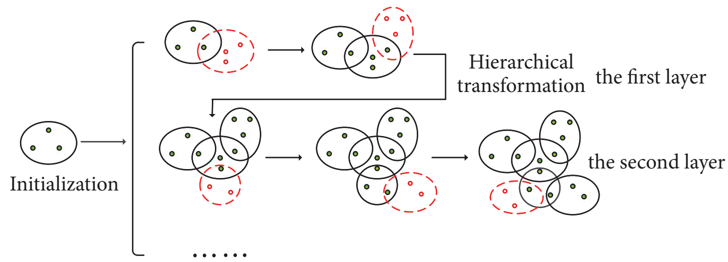


FIGURE 2: Hierarchical evolution process diagram of command and control hypernetwork.

The average field theory is used to analyze the node hyperdegree distribution of the $K(M_n + 1)$ hierarchical hypernetwork model. It is assumed that at the beginning there is a hyperedge connecting to M_0 nodes, total evolution is K layers, each layer $M = \{M_1, M_2, \cdots M_k\}$, and $C = \{C_1, C_2, \cdots C_k\}$.

When the network evolves to the time t step and at the n level of evolution, the hyperdegree of the network is $\sum d_{Ht}$, and the formula is

$$\sum d_{H_t} = M_0 + \sum_{i=1}^{n-1} C_i * M_i + \left(t - \sum_{i=1}^{n-1} C_i\right) * M_i \quad (6)$$

According to the theory of continuous field, d_H is regarded as a continuous dynamic function, and the hyperdegree $d_H(i)$ of node i can approximately satisfy the dynamic equation:

$$\begin{aligned}\frac{\partial d_H(i)}{\partial t} &\approx \frac{d_H(i)}{\sum_j d_H(j)} \\ &= \frac{d_H(i)}{M_0 + \sum_{i=1}^{n-1} C_i * M_i + \left(t - \sum_{i=1}^{n-1} C_i\right) * M_i}\end{aligned} \quad (7)$$

When M_0 is smaller and t is larger, M_0 can be ignored. The denominator of formula (7) is decomposed into

$$\frac{\partial d_H(i)}{\partial t} = \frac{d_H(i)}{\sum_{i=1}^{n-1} C_i * (M_i - M_n) + t * M_n} \quad (8)$$

For ease of calculation, order

$$a = \sum_{i=1}^{n-1} C_i * (M_i - M_n) \quad (9)$$

That is,

$$\frac{\partial d_H(i)}{\partial t} = \frac{d_H(i)}{a + t * M_n} \quad (10)$$

When each node joins the command and control hypernetwork, the initial value of the node's hyperdegree is $d_H(i) = 1$. The Derivation of Partial Differential Equations for Formula (10) is as follows:

$$d_H(i) = \left(\frac{t * M_n + a}{t * M_i + a}\right)^{1/M_n} \quad (11)$$

Since the nodes added to the hyperedge are randomly selected, the probability of hyperdegree $d_H(i)$ of the nodes is as follows:

$$P(d_H(i) < d_H) = P\left(t_i > \frac{t * M_n + a}{M_n * d_H^{M_n}} - \frac{a}{M_n}\right) \quad (12)$$

When the time interval is the same, the addition of new nodes obeys uniform distribution; that is, the t_i value has a constant probability density:

$$\rho(t_i) = \frac{1}{\sum_{i=1}^{n-1} C_i * M_i + \left(t - \sum_{i=1}^{n-1} C_i\right) * M_i} \quad (13)$$

It can be obtained:

$$\begin{aligned}&P\left(t_i > \frac{t * M_n + a}{M_n * d_H^{M_n}} - \frac{a}{M_n}\right) \\ &\quad = 1 - P\left(t_i \le \frac{t * M_n + a}{M_n * d_H^{M_n}} - \frac{a}{M_n}\right) \\ &\quad = 1 - \rho(t_i) * \left(\frac{t * M_n + a}{M_n * d_H^{M_n}} - \frac{a}{M_n}\right)\end{aligned} \quad (14)$$

The instantaneous hyperdegree distribution $P(d_H, t)$ of the network is as follows:

$$\begin{aligned}P(d_H, t) &= \frac{\partial P(d_H(t) < d_H)}{\partial d_H} \\ &= \frac{t * M_n + a}{\sum_{i=1}^{n-1} C_i * M_i + \left(t - \sum_{i=1}^{n-1} C_i\right) * M_i} d_H^{-M_n - 1}\end{aligned} \quad (15)$$

Formula (9) is introduced into Formula (15):

$$\begin{aligned}&P(d_H, t) \\ &\quad = \frac{t * M_n + \sum_{i=1}^{n-1} C_i * (M_i - M_n)}{\sum_{i=1}^{n-1} C_i * M_i + \left(t - \sum_{i=1}^{n-1} C_i\right) * M_i} d_H^{-M_n - 1} \\ &\quad = d_H^{-M_n - 1}\end{aligned} \quad (16)$$

That is to say, the hyperdegree distribution of nodes is as follows:

$$P(d_H) = d_H^{-M_n - 1} \quad (17)$$

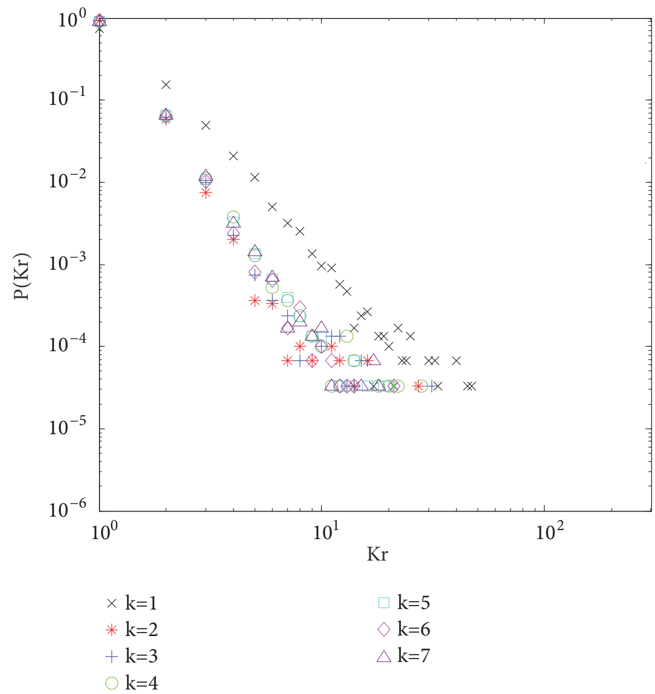


FIGURE 3: Hyperdegree distribution of different layers of hypernetwork model.

This shows that the hyperdegree of the $K(M_n+1)$ hierarchical hypernetwork model obeys the power law distribution.

4. Simulation Verification

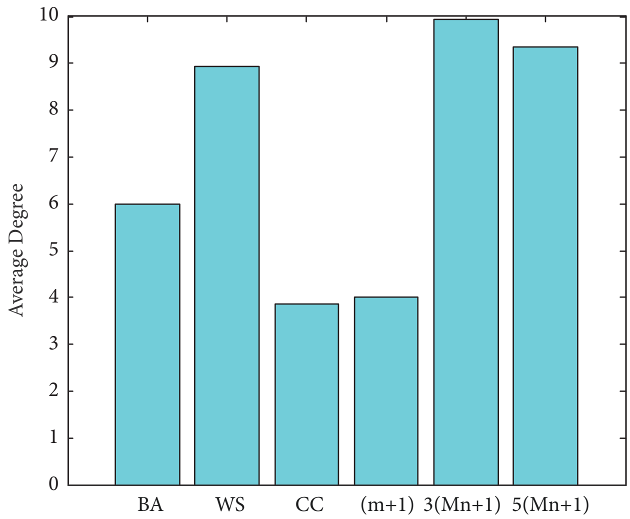
The initial state consists of three nodes and one hyperedge. Each additional node is connected to one of the existing nodes, assuming that the final number of nodes is 30,000. In order to ensure the accuracy and reliability of the experimental results, the simulation results are the average of 10 experiments. In this group of experiments, 1-7 layers of hypernetwork are modeled and simulated, respectively. The model's hyperdegree distribution is shown in Figure 3.

From Figure 3, it can be seen that the hierarchical evolution model of command and control network established in this paper conforms to power law distribution, and the network has scale-free characteristics, which is consistent with the theoretical deduction results; that is to say, it satisfies the "the rich are richer" characteristics of command and control network.

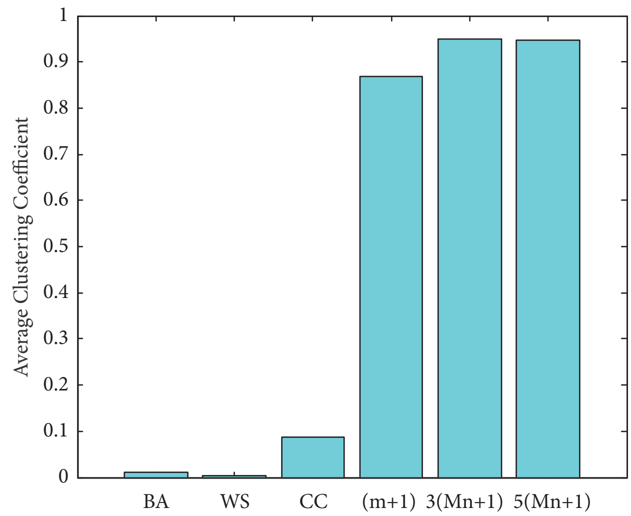
In order to further analyze the characteristics of hierarchical evolution model of command and control network, the changes of measurement indexes such as average degree, clustering coefficient, and modularity degree are simulated and analyzed. In order to make the simulation results illustrative, this paper chooses WS Small World Network [18], BA Network [19], Zhu Tao's tree command and control (CC) network [17], Hu Feng's (m+1) network [6], and the $K(M_n+1)$ hierarchical hypernetwork proposed in this paper for comparative analysis. Set the number of network nodes to 3000; each group of data were tested 10 times to get the average. The simulation results are as follows: Figures 4(a), 4(b), and 4(c).

From Figure 4(a), we can see that the average degree of $3(M_n+1)$ hierarchical hypernetwork and $5(M_n+1)$ hierarchical hypernetwork is relatively high. The greater the average degree of command and control network, the closer the connection between nodes, and the higher the efficiency of information transmission. Figure 4(b) shows that the clustering coefficients of $3(M_n+1)$ hierarchical hypernetwork and $5(M_n+1)$ hierarchical hypernetwork are significantly higher than those of other networks. The clustering coefficient of command and control network describes the degree of network structure. The larger the clustering coefficient, the closer the connection between nodes. Figure 4(c) shows that the modularity degree values of $3(M_n+1)$ hierarchical hypernetwork and $5(M_n+1)$ hierarchical hypernetwork are larger. The modularity degree of command and control network can indicate the reliability of organizational structure. The larger the modularity degree, the more reliable the organizational structure is.

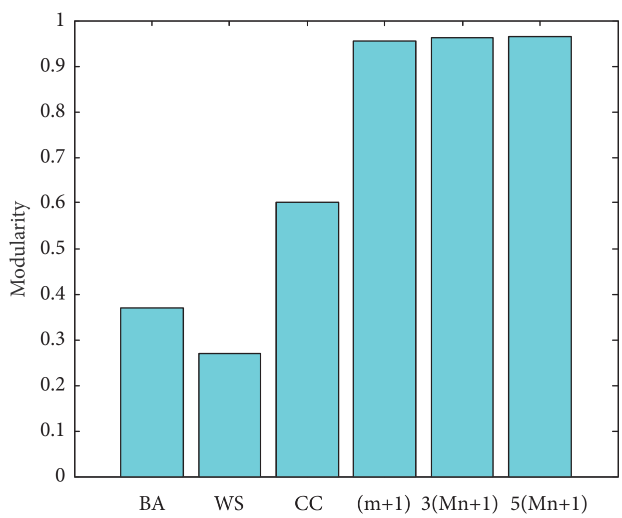
The high confrontation in battlefield puts forward higher requirements for the invulnerability of command and control network; that is, command and control network still has the ability to perform command and control tasks when encountering targeted or random attacks [11]. Natural connectivity is an important index to study the network invulnerability by calculating the weights of closed-loop numbers of different lengths and describing the redundancy of alternative routes in the network from the internal structure attributes of the network [20]. Based on this, this paper compares and analyses the changes of natural connectivity indices



(a) Average degree comparison of network models



(b) Comparison of clustering coefficients of network models



(c) Modularity degree comparison of network models

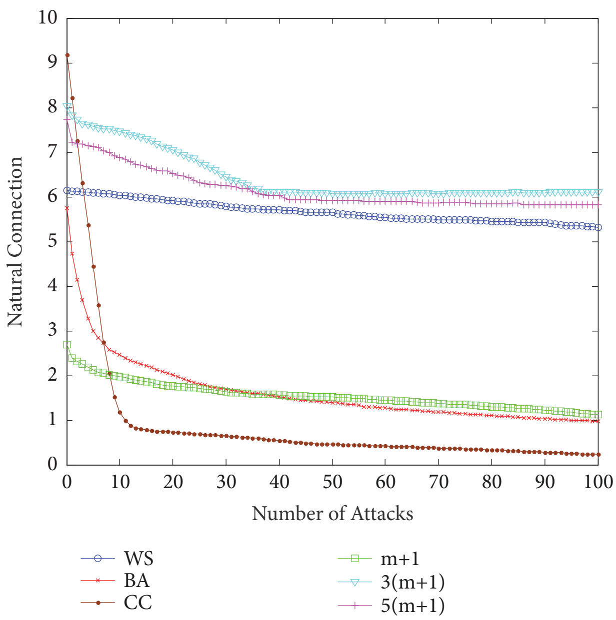
Figure 4

of WS small-world network, BA scale-free network, tree command and control network (CC), m+1 network, and 3(m+1) and 5(m+1) hierarchical hypernetwork proposed in this paper under targeted and random attacks, as shown in Figure 5.

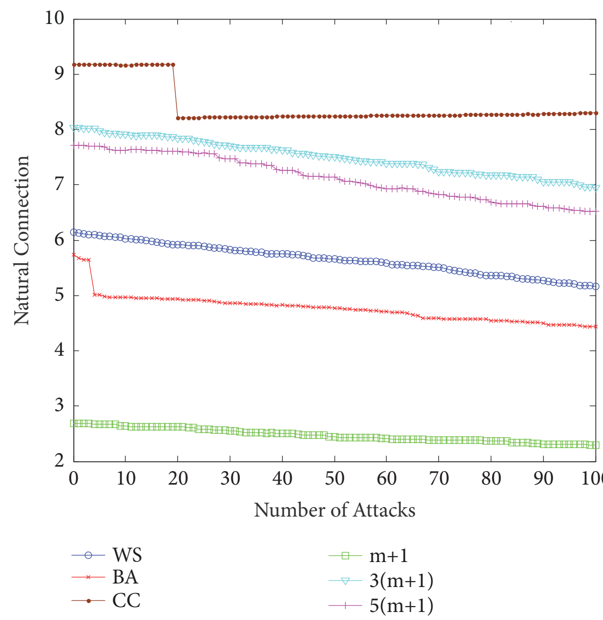
From Figures 5(a) and 5(b), it can be seen that when hypernetwork encounters targeted or random attacks, the natural connectivity of hierarchical hypernetwork is higher than that of other networks with increasing number of attacks, and the numerical value changes slowly. That is to say, the invulnerability of the hierarchical hypernetwork model proposed in this paper is obviously better than that of other network models.

5. Conclusion

Structural determinant function is the basic viewpoint of system science. In this paper, a hierarchical evolution model of command and control network based on hypernetwork is established, considering the hierarchical characteristics of command and control network, such as heterogeneous nodes and multiple links. The unique number and frequency of new nodes in different layers are considered. A strategy of joining nodes based $K(M_n + 1)$ is proposed. The hierarchical evolutionary model obeys the characteristics of scale-free network and satisfies the characteristics of command and control network that "the rich are richer." The feature scale is obviously better than the single-layer network evolutionary model, which makes the command and control network more efficient, better connectivity between nodes, and stronger reliability of organizational structure. It can guide the design of the command and control network system. The design has important reference significance for the construction of command and control network topology. At the same time, the command and control network model in this paper is constructed based on hypothesis and simplification of



(a) Comparisons of natural connectivity under targeted attack



(b) Comparison of natural connectivity under random attack

FIGURE 5

information war. The next research will continue to improve the command and control network model and simulate the dynamic information interaction between operational elements.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the Natural Science Foundation of China under Grant 91338104 and the Equipment Development Department Research Foundation of China under Grants 61400010303 and 61401310101. This work also acknowledges the paper "A Method of Key Links Identification in Command and Control Network Based on Bridging Coefficient" published in IEEE 15th International Conference on Networking, Sensing and Control (ICNSC), 2018.

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