

The Method of Health Management on Satellite Constellation Network

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Abstract— The method of health status cognition and decision on satellite constellation network based on complex network algorithms is proposed in this paper. Firstly, we describe the satellite network as a complex network, which is comprised of satellites, ground stations and links. We will prove that the satellite constellation networks have the characters of small world. Secondly, we will search for the key nodes of satellite constellation networks with evaluating algorithm of node importance. Thirdly, the health status of satellite constellation network could be evaluated according to real time operating state and decision criterion. Finally, take China's environmental and disaster monitoring and forecasting satellite constellation for example, we make the experimental analysis in order to verify the correctness of ideas proposed in this paper.

Keywords— Satellite constellation; Satellite network; Complex network; Health management; Network management

I. INTRODUCTION

With the rapid development of aerospace and electronic technique, satellite technology has been widely applied in the fields of communication, navigation and earth observation system. A single satellite could not complete the complex space task very well because of the requirements of any place and any time. Therefore, satellite constellations are emerged at right time.

Since the Transit Doppler Navigation satellite constellation is constructed at 1964, there are satellite constellations with different functions be developed, such as, the communication constellation of GlobalStar, Orbcomm and Iridium; the navigation constellation of GPS, Glonass and BeiDou; the internet constellation of SkyBridge and Orblink; the earth observation constellation of Flock Constellation and SkySat. If the links between the satellites are existed in the satellite constellation, the satellite constellation network will be constructed. However, the navigation accuracy and the validity of data transmission are close related with constellation network health, as in [1],[2].

The growing trend in network is openness, integration, high-performance and intelligentize, which will influence various aspects of network such as service, application and network itself. The new requirements, such as flexibility, reliability, conciseness and expandability, for the system of network health management have been supplied correspond to

network development, as in [3]. Four aspects, ie. detection, prediction, diagnose and repair, will be included in network health management. With the development of management technology, the traditional centralized method has been changed to active management. The intelligentized management will be realized finally. On the management platform, CiscoWorks was developed by Cisco company, which could remote manage and operate the network facility with centralized method, as protection strategy to restore network operation with the method of automatic or manual when the system was fault. HP OpenView is a representative production of HP company, which used data base, shared message and data mining technique to finish network management system. HP OpenView has compatibility for various platform, as in [5],[6]. The distributed fault management system was researched by Löb. Also, he compared centralized non-centralized with distributed diagnosed systematic in accuracy and feasibility, as in [7]. The method of cross-layer information interactive had been proposed by [8], which could improve management efficiency. On Prognostics and health management (PHM), most of technique is to solve the problems of military and aviation field. For example, large amount of experiments on satellite power system are made by PHM center which is belong to America Goebel. They use Bayesian filter method to predict the health state of power, as in [9]. With the development of the space information network recent years, the fault detecting and diagnosed technique on network had been researched based on alarm correlation, ([10],[11]), graph theory ([12]) and diagnosis in system level ([13]). Here, the method of diagnosis in system level has been widely used in the field of space information network and Ad Hoc.

The method of health status cognition and decision on satellite constellation network based on complex network algorithms is proposed in this paper. Complex network typically comprise a large number of nodes, which are interacted with edges. Connectivity and node load of network will be affected after deleting and adding nodes. Complex network is such kind of network with the character of self-organization, self-similarity, attractor, small world and scale-free. Therefore, network health status evaluation depends on health status of nodes and edges. The key problem of network evaluation is to determine the key nodes of complex network,

because there are large scale nodes in the complex network. The paper is organized as follows. Firstly, we describe the satellite network as a complex network, which is comprised of satellites, ground stations and links. We will prove that the satellite constellation networks have the characters of small world. Secondly, we will search for the key nodes of satellite constellation networks with evaluating algorithm of node importance. Thirdly, the health status of satellite constellation network could be evaluated according to real time operating state and decision criterion. Finally, take China's environmental and disaster monitoring and fore-casting satellite constellation for example, we make the experimental analysis in order to verify the correct-ness of ideas proposed in this paper.

The experimental result shows that the health management problem of satellite constellation network can be solved using complex network theory. The innovation of network health management will be referenced for large scale space network in the future.

II. FUNDAMENTAL THEORY OF COMPLEX NETWORK

The strict definition on complex network was given by professor Qian Xuesen, ie. the network with the all or part characteristic of self-organizing, self-similarity, attractor, small world and scale-free is called complex network, as in [14].

A typically network is comprised of vertexes and edges. Here, vertex may be a specific subject or a abstract thing, edge can express the relevance between individual. If we view the network from the perspective of graph theory, the network can be described by set of V and E . Where, $V=\{1,2,\dots,N\}$ is the target set which is comprised of N vertexes, and E is the set comprised of all edges in network. The vertexes can be represented as a single specific dynamic system, and the edges can be represented as a kind of relevance between individual. If the dynamic characteristic of complex network is researched in theory, the complex network can be expressed as follow as in [15]:

$$\dot{x}_i(t) = f(x_i(t)) \quad (1)$$

Eq. (1) is a mono-node state equation, which is not considerate the coupling.

A dynamic complex network for continuous system will be expressed as:

$$\dot{x}_i(t) = f(x_i(t)) + \varepsilon \sum_{j=1}^{N1} c_{ij} \Gamma(x_j(t)), \quad i = 1, 2, \dots, N, \quad (2)$$

A discrete system will be expressed as:

$$\dot{x}_i(k+1) = f(x_i(k)) + \varepsilon \sum_{j=1}^{N1} c_{ij} \Gamma(x_j(k)), \quad i = 1, 2, \dots, N, \quad (3)$$

Where,

$x_i = (x_{i1}, x_{i2}, \dots, x_{in})^T \in R^n$ is the i^{th} state vector .

$f: R^n \rightarrow R^n$ is a nonlinear smoothing vector function.

Γ is a coupling function for inscribed nodes.

ε is the coupling strength.

$C = (c_{ij}) \in R^{N1 \times N1}$ is the coupling structure matrix and topology structure of network. They can be defined as:

$$C = \begin{cases} 1, & \text{there is a edge between nodes } i, j (i \neq j); \\ 0, & \text{there is not a edge between nodes } i, j (i \neq j); \\ -\sum_{j=1}^{N1} c_{ij}, & i = j. \end{cases} \quad (4)$$

Where, C is a irreducible matrix for the connected network.

All of information about network structure is contended by matrix C .

All network has two characteristics, ie. definiteness and randomness. The law of randomness is hidid in statistical property. Therefore, it is very important that describe the characteristic of complex network with statistical method. Generally, we use degree distribution, average path length and clustering coefficient to describe basic static geometry ([16]).

A. Degree Distribution

Degree distribution is a key statistical property on network. The degree of node is defined as the number of its edge in network. Degree distribution is described by degree distribution function $p(k)$. The $p(k)$ represents a node probability which degree is k , when we select the node randomly. Degree distribution can reflect directly the degree of uniform distribution on network connecting. A regular lattice has a simple degree sequence, because the degree of all node is same and with poisson distribution.

B. Average Path Length

The distance d_{ij} between node i and j is defined as the number of edge of the shortest path connected the two nodes. In particular, the maximal distance between any two nodes is defined as network diameter. The average distance between two nodes is defined as average path length L . During network research, the important discovery is that the average path length is shorter than the one we imagine in the most of large scale real network, ie. the small-world Effect. For example, the average path length for WWW(World Wide Web) is less than 20, which is with billions nodes. The calculation method of average path length is expressed as follow:

$$L = \frac{1}{N(N-1)} \sum_{i,j \in N, i \neq j} d_{ij} \quad (5)$$

Where, N is number of network nodes. The degree of nodes separation is described by average path length.

C. Clustering Coefficient

The clustering characteristic means that it maybe neighbor between the neighbor node of node i . Assume that node i is connected with other nodes with its k_i edges, therefore, the k_i nodes will become the neighbor of node i . The great number of edge between the k_i nodes are $k_i(k_i-1)/2$. The clustering coefficient C_i is defined as the ratio of actual number of edge E_i between k_i nodes to $k_i(k_i-1)/2$. That is

$$C_i = \frac{2E_i}{k_i(k_i - 1)} \quad (6)$$

The clustering coefficient C is defined as the average value of all nodes clustering coefficient.

III. FEATURE ANALYSIS ON SATELLITE CONSTELLATION NETWORK

Satellite constellation is a satellite set, which is composed of multiple satellites with a regulation and shape. The satellites can provide the coverage performance. It is a basic operation mode of multi-satellite corporation mission. The characteristic of satellite constellation is better than the one of single satellite during the engineering application.

A. Predictability of Network Topology

A satellite network is composed of satellite nodes moved on different orbital plane. The network is formed through ISLs (Inter-Satellite-Links) which is between satellite nodes. It is different from ground network that satellite network is composed of satellite nodes with different orbital feature and payload. The ISLs will handover incessant, because of satellite moving. Therefore, the network topology will be changed with the ISLs handover.

The basic orbit parameter concludes six elements for single satellite. Therefore, the topology and variation tendency could be predicted for satellite constellation network, even though when the constellation configuration has been changed.

B. Periodicity of Configuration Changing

The relative relationship between satellites will be periodic changed in a constellation network, because a satellite will move on predetermined orbit. It is closely related between the topology changing and constellation configuration.

The relative position between satellites is changed periodically, since satellites in the constellation moving according to a certain orbital period. Therefore, the constellation network topology is periodicity.

C. Feature of Health Management

The data source of satellite constellation PHM is from telemeter and measuring system. The state information, such as power, thruster, transponder etc., on board can be collected through various kinds of sensor. The date of range, velocity and angle can be obtained by measuring facility installed in ground station. Also, we can integrate inter-satellite data and ground-satellite data to determine the orbit and constellation configuration. One of the PHM means is to operate satellite through telecommand channel. The decision will be realized by telecommand channel between inter-satellite or ground-satellite to target satellite in the form of constructions.

IV. HEALTH MANAGEMENT MODEL ON SATELLITE CONSTELLATION NETWORK

In essence, the foundation of PHM is to establish the key node model. The network key node is analyzed making use of graph theory and complex network theory. Usually, the importance of network node is evaluated with degree or

intensity. The maximum of node degree or node strength will be key network node.

The node degree is defined as the number of edges connected with adjacent node directly. In the constellation network G with N nodes and adjacent matrix $A=(a_{ij})_{N \times N}$, the degree of node i can be expressed as

$$k_i = \sum_{j=1}^N a_{ij} \quad (7)$$

Eq. (17) is normalized as follow

$$d_i = \frac{k_i}{\sum k_i} \quad (8)$$

Node strength is in view of the weighted networks. In the constellation network G with N nodes and weight matrix $W=(w_{ij})$, the strength of node i can be expressed as

$$s_i = \sum_{j=1}^N w_{ij} \quad (9)$$

Eq. (19) is normalized as follow

$$q_i = \frac{s_i}{\sum s_i} \quad (10)$$

In constellation network, node importance evaluation method includes: the evaluation method based on mutual information, the evaluation method based on natural connectivity and the evaluation method of topology survivability based on close to central degree.

The node importance is evaluated through quantity of information for the method of mutual information. The information included in node is determined by node degree.

Natural connectivity method from the internal structure properties of network, by calculating the number of closed paths of different lengths in network to depict the redundancy of alternative paths in a network, the mathematical form can be derived from the network characteristic of adjacency matrix spectrum directly.

Center of the research emphasis is to analyze the nodes in the network status, one of the indexes of betweenness, aggregation coefficient is in part reflects the nodes in the network centrality, the importance of nodes in network mainly depends on its position in the network.

The results show that the satellite network topology based on close to center anti-destroying ability evaluation method can accurately determine the importance of nodes in the two topologies as in [17,18,19,20].

V. MODELING AND ANALYSIS OF DISASTER MONITORING MINISAT CONSTELLATION

A. Overview

There are two problems with single remote sensing satellite used for disaster monitoring and prediction. Firstly, It is limited in number and variety of payload; Secondly, the long return period can't meet the requirements of monitoring and prediction of observation.

Compared with the traditional spacecraft, small satellite has a high level of integration, superior performance, low cost, small volume and quality, as well as the advantages of short development cycle. The minisat constellation can achieve real-time, dynamic monitoring and establish technical support system for disaster prevention. At the same time, it can improve the ability of integrated disaster reduction goals.

The end of last century, China began construction the environment and disaster monitoring and prediction of small satellite constellation for disaster monitoring and prediction and the ecological environment monitoring. The development scheme of four optical and four synthetic space radar satellites is proposed. The environment and disaster monitoring and prediction of small satellite constellation would be established with two stages. For the first stage, two optical remote sensing satellites and one synthetic aperture radar satellite were launched, which can realize preliminary ability of disaster monitoring. For the second stage, four optical remote sensing satellites and four synthetic aperture radar satellites were launched, which can realize the dynamic monitoring of China and even global disaster.

B. Designing of Constellation Network

If the ISLs are established between the constellation satellites, the constellation network could be built. One ISL antenna will be installed on-board according to visibility between satellites in constellation network, which is shown in Figure 1. Figure 2 shows the coverage of China.

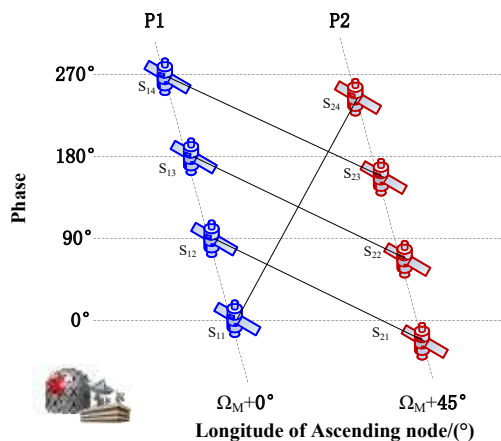


Figure 1. The schematic diagram of constellation network

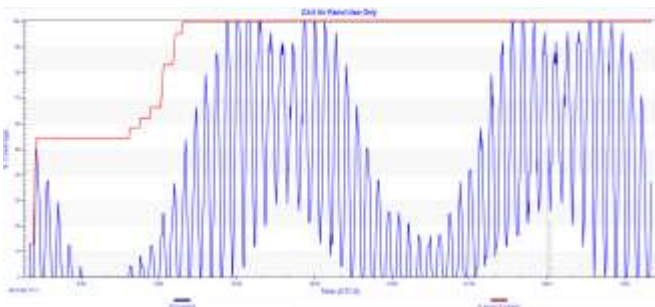


Figure 2. The schematic diagram of coverage of China

The constellation network should be connected with ground station network, since the constellation network is need to be operated by ground station. The schematic diagram of integrated constellation and ground is shown in Figure 3. Figure 4 is conceptual diagram of PHM model.

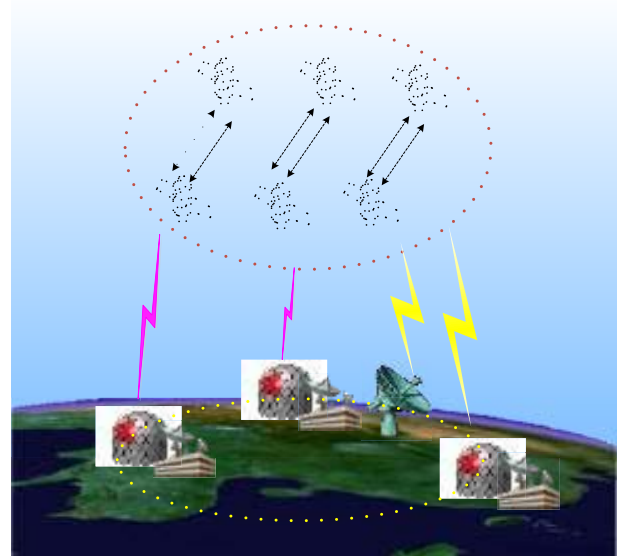


Figure 3. The schematic diagram of PHM.

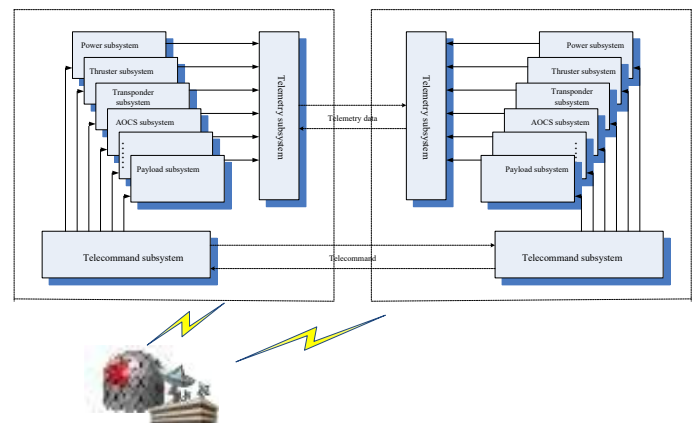


Figure 4. The conceptual diagram of PHM model.

C. The Analysis of PHM Based on important node

We will analysis the performance of disaster monitoring minisat constellation according to the model in Eq.(7).

There are two kinds of node in the disaster monitoring minisat constellation. They are satellite and ground station. There is a relative movement between two nodes. There are several sub-nodes for satellite nodes, which is described in Figure 5. Figure 6 shows the network model on the level of satellite and ground station. The network is composed of eleven nodes and twenty-eight edges; its average degree is 5.091.

The clustering coefficient and key path in Figure 5 is as follow

$$L_{rand} = \frac{\ln n}{\ln k} = \frac{\ln 11}{\ln 5.091} = 1.47$$

$$L_{regular} = \frac{n(n+k-2)}{2k(n-1)} = \frac{11*(11+5.091-2)}{2*5.091*(11-1)} = 1.52$$

$$C_{rand} = \frac{k-1}{n} = \frac{5.091-1}{11} = 0.372$$

$$C_{regular} = \frac{3(k-2)}{4(k-1)} = \frac{3*(5.091-2)}{4*(5.091-1)} = 0.567$$

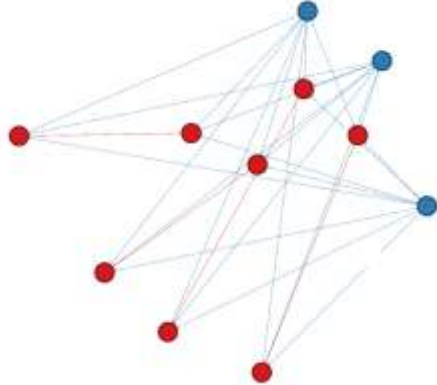


Figure 5. The network model on the level of satellite and ground station

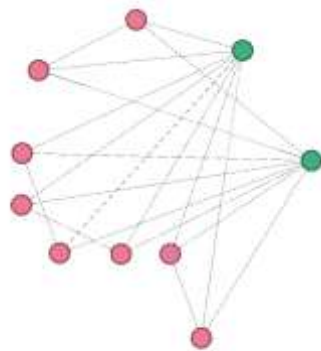


Figure 6. The network model on the level of satellite and ground station with one link break down.

Assume, the ground station with high degree nodes breaks down. The network model diagram is shown in Figure 6 which is composed of ten nodes and twenty edges. The clustering coefficient and key path in Figure 14 is as follow

$$L_{rand} = \frac{\ln n}{\ln k} = \frac{\ln 10}{\ln 4} = 1.66$$

$$L_{regular} = \frac{n(n+k-2)}{2k(n-1)} = \frac{10*(10+4-2)}{2*4*(10-1)} = 1.67$$

$$C_{rand} = \frac{k-1}{n} = \frac{4-1}{10} = 0.3$$

$$C_{regular} = \frac{3(k-2)}{4(k-1)} = \frac{3*(4-2)}{4*(4-1)} = 0.5$$

It is observed that the key path is bigger than which is in Figure 5 and the clustering coefficient is smaller than which is in Figure 5.

In the space level, we have network configuration shown in Figure 7. There eight nodes and twelve edges inside the satellite. Its average degree is 3.

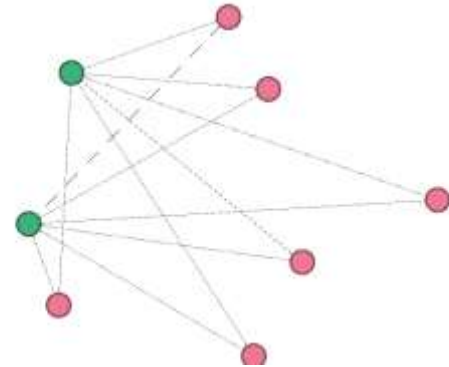


Figure 7. The network model inside satellite.

The characteristic parameters are as follow:

$$L_{rand} = \frac{\ln n}{\ln k} = \frac{\ln 8}{\ln 3} = 1.89$$

$$L_{regular} = \frac{n(n+k-2)}{2k(n-1)} = \frac{8*(8+3-2)}{2*3*(8-1)} = 1.71$$

$$C_{rand} = \frac{k-1}{n} = \frac{3-1}{8} = 0.25$$

$$C_{regular} = \frac{3(k-2)}{4(k-1)} = \frac{3*(3-2)}{4*(3-1)} = 0.375$$

Assume, the telecommand subsystem on board with high degree nodes is break down; its network configuration is changed to Figure 8. The network is composed of seven nodes and six edges with average degree of 1.714.

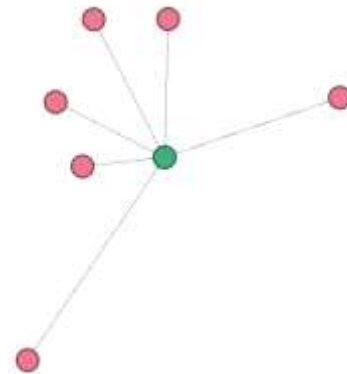


Figure 8. The network model with telecommand subsystem breaking down.

The characteristic parameters are as follow:

$$L_{rand} = \frac{\ln n}{\ln k} = \frac{\ln 7}{\ln 1.714} = 3.61$$

$$L_{regular} = \frac{n(n+k-2)}{2k(n-1)} = \frac{7*(7+1.714-2)}{2*1.714*(7-1)} = 2.29$$

$$C_{rand} = \frac{k-1}{n} = \frac{1.714-1}{7} = 0.102$$

$$C_{regular} = \frac{3(k-2)}{4(k-1)} = \frac{3*(1.704-2)}{4*(1.704-1)} = -0.32$$

In the level of network, the network model is shown in Figure 9. It is composed of sixty-four nodes and one hundred edges. Its average degree is 3.125.

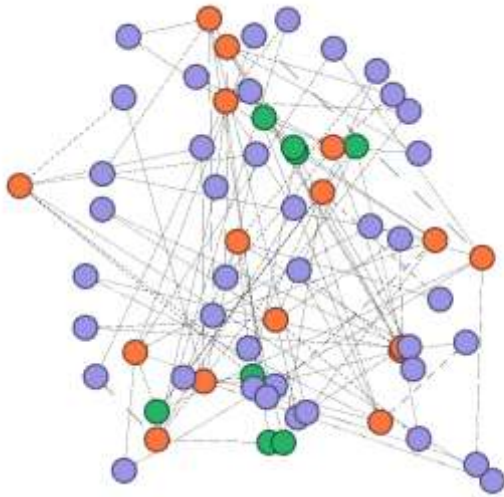


Figure 9. The network model of space based network.

The characteristic parameters are as follow:

$$L_{rand} = \frac{\ln n}{\ln k} = \frac{\ln 64}{\ln 3.125} = 3.65$$

$$L_{regular} = \frac{n(n+k-2)}{2k(n-1)} = \frac{64*(64+3.125-2)}{2*3.125*(64-1)} = 10.59$$

$$C_{rand} = \frac{k-1}{n} = \frac{3.125-1}{64} = 0.033$$

$$C_{regular} = \frac{3(k-2)}{4(k-1)} = \frac{3*(3.125-2)}{4*(3.125-1)} = 0.313$$

If the telecommand subsystem with high degree nodes breaks down, the network configuration is shown as Figure 10. The network is composed of sixty-three nodes and ninety four edges. Its average degree is 2.984.

The characteristic parameters are as follow:

$$L_{rand} = \frac{\ln n}{\ln k} = \frac{\ln 63}{\ln 2.984} = 3.79$$

$$L_{regular} = \frac{n(n+k-2)}{2k(n-1)} = \frac{63*(63+2.984-2)}{2*2.984*(63-1)} = 11.06$$

$$C_{rand} = \frac{k-1}{n} = \frac{2.984-1}{63} = 0.047$$

$$C_{regular} = \frac{3(k-2)}{4(k-1)} = \frac{3*(2.984-2)}{4*(2.984-1)} = 0.372$$

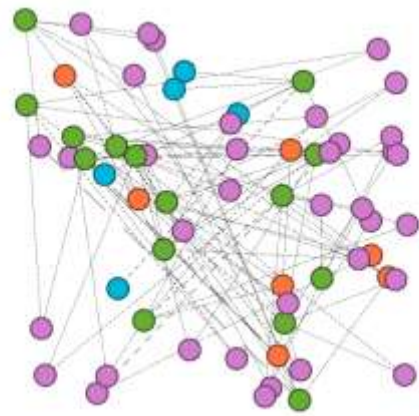


Figure 10. The network model with telecommand subsystem breaking down.

To sum up as following.

TABLE 1. THE SIMULATION RESULT WITH GEPHI TOOL

	Number of nodes	Number of edges	Average degree	Key path	Clustering coefficient
Model on the level of satellite and ground station	11	28	5.091	1.47	0.372
Model with one ground station breaking down on the level of satellite and ground station	10	20	4	1.66	0.3
Model of inside satellite	8	12	3	1.89	0.25
Mode with telecommand subsystem breaking down inside satellite	7	6	1.714	3.61	0.102
Model on the level of space	64	100	3.125	3.65	0.033
Model with the telecommand subsystem breaking down on the level of space	63	94	2.984	3.79	0.047
Model on the level of integrated space and ground station	67	124	3.701	3.21	0.0403
Model with one link breaking down on the level of integrated space and ground station	66	116	3.515	3.33	0.038

VI. CONCLUSION

The health management method of satellite constellation is analyzed in view of network configuration this paper. The model, included ISLs, network nodes and network topology, is established based on the characteristic of network topology and configuration. The model of PHM on satellite constellation is established according to the fundamental theory of network science.

Finally, we take the CDMMC (China Disaster Monitoring Minisat Constellation) as an example. The characteristics both normal and fault are analysed with Gephi Tool on the level of satellite-ground, interior satellite, space network and integrated space and ground station. The results show that: when the high degree nodes are broken down, the parameters both key path and clustering coefficient are changed compared with the normal situation. Therefore, it can be determined that the connectivity of network is weakened.

Therefore, it is can save cost and improve work efficiency that to monitor and control the high degree nodes during health management of satellite constellation.

It is a complex mission of health management. The further research is to explore the advanced method to manage the larger scale space network.

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