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Network Characteristics Analysis of Air Traffic Management Technical Support System Based on Multi-source Weighting

Kai Fan[1], Song Han[1,*], Wei Li[1], Lisha Yu[1], Jiayu Quan[1], Peng Li[1]

Fan K https://orcid.org/0000-0002-7438-564X
Han S https://orcid.org/0000-0001-8598-6558
Li W https://orcid.org/0000-0002-3786-4959
Yu L https://orcid.org/0000-0002-6190-9141
Quan J https://orcid.org/0000-0002-0118-9656
Li P https://orcid.org/0000-0003-2226-0500

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ABSTRACT: In order to make reasonable suggestions for the expansion of the Air Traffic Management Technical Support System (ATMTSS), it is necessary to conduct a comprehensive analysis of the ATMTSS network. This paper constructs a multi-source weighted ATMTSS network which considers the working characteristics and geographical locations of the facilities. The complex network metrics, such as degree, node strength, clustering coefficient, average path length, diameter, and the improved Fast-Newman (FN) algorithm, are used in the analysis of the network. The results show that the ATMTSS network is a complex network with small-world characteristics and random characteristics, and that the distribution of ATMTSS network support capability is not the same as the topology network structure. The weighted network is looser than the non-weighted network. The air traffic management in remote areas is less affected by facilities than that in developed areas.

KEYWORDS: Complex network, Community structure, Air traffic management, Geographical location.

INTRODUCTION

The Air Traffic Management (ATM) system is the prerequisite to ensure the safety and smooth operation of an aircraft network, and the ATM Technical Support System (ATMTSS) is an important component of the ATM system. ATMTSS includes communication, navigation, and surveillance equipment to complete aircraft navigation, air-to-ground communication, aircraft monitoring, and other functions. When any ATMTSS device is broken, it is very likely to cause the collapse of ATM in the local area. Since air traffic flow is increasing and ATMTSS network is developing, local accidents would result in complicated events, even the system paralysis in a large airspace.

At present, the researches on ATMTSS network are mainly focused on the analysis of the statistical characteristics of ATMTSS. Wu *et al.* (2016) used the complex network theory to analyze the flexibility, robustness, and efficiency of ATMTSS network in six flight information regions of China. Feng *et al.* (2015) used betweenness to analyze the navigation system in southwest China. Cheung and Gunes (2013) used the complex network theory to analyze the statistical characteristics of American aircraft

1. Sichuan University – School of Aeronautics and Astronautics – Chengdu/Sichuan – China.
Correspondence author: hansongchen@scu.edu.cn
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transportation network. Metha *et al.* (2012) used low frequency spectrum to analyze the clustering coefficient of American airport network. Dang and Li (2015) analyzed the characteristics and invulnerability of air route network in China. Zhang *et al.* (2010) analyzed the clustering coefficient and shortest path of airport network in China. Some studies used weighted network to analyze the topology of the ATMSS. ATMTSS concerns the weighted network features that the support capability is the weight of the network. Huang (2013) used complex network theory to analyze the complexity of ATMTSS network and provide the optimal service configuration model with the genetic algorithm. Zeng *et al.* (2011) used the complex network theory to analyze the air route network, which is weighted by air route distance. In summarize, the community structure is an inherent attribute of the real network and it can reflect the node aggregation of the network.

In addition to statistical characteristics, only a few studies are focused on the community structure of the ATMTSS network. The community structure of this network can reflect its development and function structure. Many scholars (Luo *et al.* 2016, Ding *et al.* 2013, Blenn *et al.* 2012) have studied the community structure in other kinds of networks. And many algorithms have been proposed, just like the Girvan-Newman (GN) algorithm (Newman and Girvan 2004), the Fast Newman (FN) algorithm (Newman 2004), and the Kernighan-Lin (KL) algorithm (Kernighan and Lin 1970). These algorithms only apply to non-weighted networks. Chen and Xu (2013) modified the Clauset-Newman-Moore (CNM) algorithm and applied geographical distance to the weight of network. Li (2016) and Han *et al.* (2010) modified the algorithm to use it in the weighted network. But they cannot use the distance information into the weight. The idea of the CNM algorithm is similar to the FN algorithm. The difference between the FN algorithm and the CNM algorithm is that the CNM algorithm constructs the modular increment matrix and the maximum heap. However, the computing step in CNM is more complicated than in the FN algorithm.

In this paper, a weighted ATMTSS network model is presented, and the working characteristics and geographical location of devices are fully considered. The topological properties and functional characteristics of the network are analyzed by using non-weighted and weighted statistical characteristics. Then the improved FN algorithm is used to analyze the community structure of the ATMTSS network, and the results reveal the weakness of network construction from the aspect of support capability.

ATMTSS NETWORK MODEL CONSTRUCTION

The ATMTSS includes communication, navigation, and surveillance devices. Only when the three devices cooperate with each other the system can work properly. Due to the different working mode and operating principle of the three kinds of device, they play different roles in the aircraft flight. Before constructing the ATMTSS network model, the working principle and cooperative operation mechanism of the device should be understood.

MODEL CONSTRUCTION USING THE WORKING PRINCIPLE

According to the different functions of the devices in ATMTSS, these are divided into three categories: communication, navigation, and surveillance. They cooperate with each other in air traffic control. Because the system is hierarchical, complex, and diverse, we need to analyze each kind of device. Surveillance devices monitor aircraft movements in the airspace. There are Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), and Automatic Dependent Surveillance-Broadcast (ADS-B) etc. (Wu *et al.* 2016). This kind of device can obtain information about the aircraft's identification code, flight height, speed, distance, and location. Among them, PSR and SSR are often fitted together, and the aircraft information can be obtained by transmitting the beam. ADS-B broadcasts information on avionics through the data chain, and it finally monitors aircrafts with the same image as the radar.

The two-way audio function and signal communication between aircraft and ground aviation personnel (navigation control, signing, maintenance etc.) are mainly accomplished by communication devices. Communication devices include High Frequency (HF) communication system, Very High Frequency (VHF) communication system, call system, and audio system. The VHF is mainly used for air-ground communication and air-air communication, and HF is more suitable for long distance broadcasting and radio communication. VHF is the main communication equipment of civil aviation and it can spread no more than 200 km (Feng 2016).

Navigation devices are mainly used to guide the aircraft to take off, land, and cruise. They also provide the aircraft with information, such as distance, to ensure the aircraft to fly correctly along the given flight path. At present, the navigation system of civil aviation is still mainly based on the ground navigation system. The ground navigation system mainly includes Non-Direction Beacon (NDB), Very high frequency Omni-directional Range (VOR), and Distance Measuring Equipment (DME). VOR and DME are generally installed on the same site, and they're in charge of navigation on the route (Wu *et al.* 2016, Feng 2016).

When constructing the ATMTSS network model, it is necessary to consider the relationship between devices and routes, so that the network topology can be truly carried out. In this paper, VOR/DME are used as the navigation device, PSR/SSR as the surveillance device, and VHF as the communication device to construct the network. We're taking VOR/DME as the nodes and the route protected by the support devices as the edges. Each edge is supported by three kinds of devices, and the support capability of these devices jointly determines the weight of the edge. Therefore, the ATMTSS network can be expressed as (Eq. 1):

$$G = (V, E, R, S) \tag{1}$$

where $V = (v_1, v_2, ...v_n)$ is the set of nodes; $E = (e_1, e_2, ...e_m)$ is the set of routes; R is the adjacency matrix; and S is the set of support capability weight on the routes.

R is expressed as:

$$R_{n\times n} = \begin{bmatrix} 0 & r_{11} & \cdots & r_{1n} \\ r_{21} & 0 & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & 0 \end{bmatrix}$$

When a route between nodes i and j exists, the value of r_{ij} is 1, otherwise it is 0.

$S = (s_{ij} \mid i, j, \mathrm{E}\ (0,n))$ represents the set of support capability weight on the routes. After normalization, the weight of the route between nodes i and j in the network can be expressed as (Eq. 2):

$$s_{ij} = aX_{ij} + bY_{ij} + cZ_{ij} \tag{2}$$

where X_{ij} is the support capability weight of PSR/SSR; Y_{ij} is the support capability weight of VHF; and Z_{ij} is the support capability weight of VOR/DME. a, b, and c represent the ratio of the weight of three kinds of devices. $a + b + c = 1$; considering the synergy of the three devices, a, b, and c can be set to be equal.

PSR/SSR weight selection principle

PSR/SSR are mainly installed in the vicinity of the airport and the main routes. Reliability can be used to describe the support capability of PSR/SSR. Reliability refers to the probability that the device can work normally after having been working for a period. The radar's working life is subject to the Weibull Distribution (Peto and Lee 1973). There are early failure period, accidental failure period, and loss failure period. Therefore, the reliability can be expressed as (Eq. 3):

$$W_1(t) = e^{-\left(\frac{t-\gamma_1}{\beta_1}\right)^{\alpha_1}} \tag{3}$$

where α_1 is the shape parameters of PSR/SSR; β_1 is the life span of PSR/SSR; and γ_1 is the first failure time of PSR/SSR.

The reliability of the route between nodes can be used to represent the weight of PSR/SSR. However, the route may be supported by more than one device. As it is shown in Fig. 1 (a), the route between nodes i and j is supported by PSR/SSR1 and PSR/SSR2. The support range of PSR/SSR is r1. Therefore, the concept of "total reliability" is introduced below, which can be expressed as (Eq. 4):

$$X_{ij} = 1 - \prod_{m_1=1}^{c_1} (1 - W_1(\mathrm{t})_{m_1}) \tag{4}$$

where c_1 is the number of PSR/SSR devices that support the same route between nodes *i* and *j*; $W_1(\mathrm{t})_{m1}$ is the reliability of PSR/SSR m_1; and $\Pi_{m1\text{-}1}^{c1}$ $(1-W_1(\mathrm{t})_{m1})$ is the total unreliability on the route *ij*. Because the overlap degree of the signal on the same route may be different, the average value of the signal overlap is calculated based on half the length of the route.

As is shown in Fig.1 (b), the PSR-SSR signal is limited by the terrain, and the coverage of the signal needs to be calculated. Cover angle and cover distance are as follows (Eq. 5 and Eq. 6) (Feng *et al.* 2015):

$$\theta_s = \frac{h_s - h_a}{17.45 d_s} - \frac{d_s}{296.5} \tag{5}$$

$$R_s = \sqrt{(R_e + \tan\theta_s)^2 + 2R_e(h_s - h_a)} - R_e \tan\theta_s, R_e = 4R_{\mathrm{na}} / 3 \tag{6}$$

where θ_s is the cover angle; h_s is the height of the plane; h_a is the height of the device antenna; d_s is the distance from the obstacle to the device; R_s is the cover distance; and R_{na} is the radius of coverage under free space.

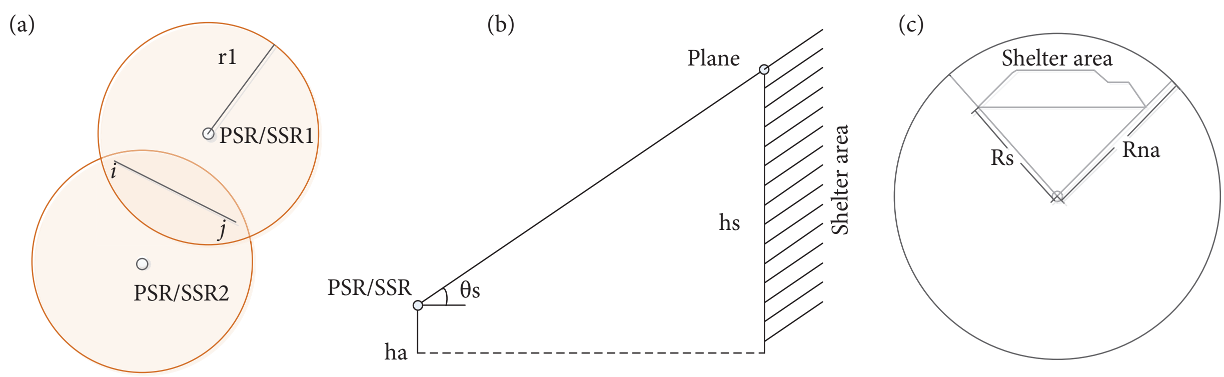


Figure 1. Primary Surveillance Radar/Secondary Surveillance Radar (PSR/SSR) coverage principle. (a) Route covered by two devices; (b) cover angle and cover distance.

VHF weight selection principle

In ATM, airspace is divided into many sectors, and each sector has its own VHF signal coverage. The VHF's working life is subject to the Weibull Distribution, just like PSR/SSR. So, the concept of reliability also applies to VHF. It can be expressed as (Eq. 7):

$$W_2(t) = e^{-(\frac{t-\gamma_2}{\beta_2})^{\alpha_2}} \tag{7}$$

where α_2 is the shape parameters of VHF; β_2 is the life span of VHF; and γ_2 is the first broken time of VHF.

Similar to PSR/SSR, a single route may be covered by multiple VHF signals. And the reliability can be used to represent the weight of VHF. As it is shown in Fig. 2, the route in the sector is supported by VHF1 and VHF2. The support range of VHF is r2. The total reliability on the route between nodes *i* and *j* can be expressed as (Eq. 8):

$$Y_{ij} = 1 - \prod_{m_2=1}^{c_2} (1 - W_2(\mathrm{t})_{m_2}) \tag{8}$$

where c_2 is the number of VHF devices that support the same route between nodes *i* and *j*; $W_2(\mathrm{t})_{m2}$ is the reliability of VHF m_2;

and $\Pi_{m2\text{-}1}^{c2}(1-W_2(t)_{m2})$ is the total unreliability on the route *ij*. The average value of the overlapping signal is also calculated based on half of the length of the route.

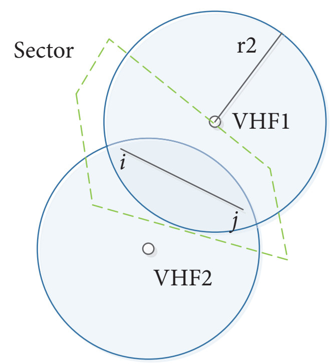


Figure 2. Route in a sector covered by two Very High Frequency (VHF) signals.

VOR/DME weight selection principle

The mission of VOR/DME is navigating the aircraft. In ATM, the support capability of the VOR/DME station is related to its role. The more important the station is, the greater the degree it has. Degree represents the number of edges connected with this node while the support capacity is inversely proportional to the length of the route. So, the weight of VOR/DME can be expressed as (Eq. 9) (Qin and Dai 2007, Feng 2016):

$$Z_{ij} \propto \frac{k_i k_j}{l} \tag{9}$$

where k_i and k_j are the degrees of nodes *i* and *j*; and *l* is the length of this route. Through the above-mentioned model construction and weight selection principle, the ATMTSS weighted network model can be successfully constructed. According to the weighted network model, the topological structure and function of the network can be analyzed with appropriate measurement indexes.

ATMTSS NETWORK MEASUREMENT INDEXES

In order to make a comprehensive analysis of ATMTSS network, non-weighted and weighted measurement indexes, such as degree, node strength, clustering coefficient, average path length, and diameter etc., are adopted. The topological structure of the network can be analyzed by non-weighted statistical features, and the function of the network can be analyzed by the weighted feature analysis.

Degree and degree distribution

Degrees are the physical quantities that express the importance of nodes in the ATMTSS network. k_i , which is the degree of node *i*, is defined as the number of routes connected by this node, and it can be expressed as (Eq. 10):

$$k_i = \sum_j e_{ij} \tag{10}$$

where e_{ij} is the route between nodes *i* and *j*. The degree distribution in the network is expressed by the distribution function $p(k)$, which describes the probability that the degree of an arbitrary choice of nodes happens to be k . If the degree distribution of a network satisfies the power law distribution, the network has a random feature.

Clustering coefficient

The clustering coefficient is the characteristic physical quantity of the ATMTSS network. According to the concept of degree, if the node i connects with other nodes by k_i routes, those nodes are called the neighbors of node i. The maximum number of routes that its neighbors can form is $k_i(k_i - 1)/2$. And the clustering coefficient c_i refers to the ratio of the actual number of routes between all the neighbors' nodes and the total number of possible routes. It can be expressed as (Eq. 11):

$$c_i = 2e_i / (k_i(k_i - 1)) \tag{11}$$

where e_i is the number of routes that the neighbors of node i formed. The clustering coefficient C of the whole network is the average of all nodes clustering coefficients. Since $0 < C < 1$, when and only if all nodes are isolated nodes, $C = 0$; and when and only if the network is globally coupled in a manner that any two nodes in the network are directly connected, $C = 1$.

Node strength and node strength distribution

Node strength is also called node weight, which refers to the sum of all the route weights connected to this node. It is the concept extension of the degree in a weighted network, and it can be expressed as (Eq. 12):

$$S_i = \sum_{j \in \Upsilon_i} s_{ij} \tag{12}$$

where s_{ii} is the weight of route that connects the nodes i and j. The node strength reflects the neighborhood information of nodes in the network. Taking ATMTSS network as an example, the node strength represents the sum of the support capabilities of a node in the network. The node strength distribution in the network is expressed by the distribution function $p(s)$, which describes the probability that the node strength of an arbitrary choice of nodes happens to be s.

Weighted clustering coefficient

The weighted clustering coefficient is the extension of the clustering coefficient in a weighted network. It represents the degree of connection between nodes and adjacent nodes. It can be expressed as (Eq. 13):

$$c^s_{0,i} = \sum_{j,k} (s'_{i,j} s'_{j,\mathrm{k}} s'_{k,i}) / (k_i(k_i - 1)) \tag{13}$$

where k_i is the degree of node i; and $s'_{ij} = s_{ij}/\max(s_{ij})$ is the normalized weight of the route, which is connected to the node i. The weighted clustering coefficient C^s of the whole network is the average of all nodes weighted clustering coefficients.

Average path length and network diameter

The average path length is the physical quantity of the small-world characteristics of ATMTSS network. The network distance between two nodes i and j in the network is defined as the number of edges connecting the shortest routes of these two nodes. The maximum distance between any two nodes in the network is called the diameter D of the network. It is expressed as (Eq. 14):

$$D = \max_{i,j} d_{ij} \tag{14}$$

where d_{ij} is the number of routes between nodes i and j .

The average path length of the network L is the average of the distance between all couple nodes. It is expressed as (Eq. 15):

$$L = \frac{1}{\frac{1}{2}N(N+1)} \sum_{i \geq j} d_{ij} \tag{15}$$

where N is the total number of nodes in the network. The average path length of the network is also called the characteristic path length of the network.

Community structure

As a special network measurement index, community structure can reflect the function and performance of the network. By analyzing the community structure of ATMTSS network, the key area and development of ATMTSS network can be understood. Community structure is a common feature in real networks, which means that nodes in the network can be divided into different groups, the intra-connections in a group are compact, and the interconnections between different groups are sparse (Wang *et al.* 2008). The determination of community is difficult by using topology of the network. Newman and Girvan (2004) introduced a function called modularity to measure the quality of network community structure. The number of communities that they divide is k. Defining a symmetric matrix:

$$P \in R_{k \times k}$$

In which, elements p_i represent the proportion of routes that connect the nodes of two different communities in the network. These two communities are set to x and y. The sum of the elements on the diagonals in the matrix is expressed as:

$$t = \sum_{i=1}^{c} p_{ii}$$

It represents the proportion of routes that connect the nodes of community m in the network. The sum of the elements in each row (or column) is expressed as:

$$h_i = \sum_{j=1}^{c} g_{ij}$$

And it represents the proportion of the routes that connect the nodes of community x from the outside in the network. So, the measure of modularity can be expressed as (Eq. 16):

$$Q = \sum_{i=1}^{c} (p_{ii} - h_i^2) = t - \left\| P^2 \right\| \tag{16}$$

where $||P^2||$is the sum of all the elements in P^2. The modularity is the number of edges falling within communities minus the expected number in an equivalent network with routes placed at random (Wang *et al.* 2008). The modularity ranges from 0 to 1. It is high for good community divisions and low for bad ones.

In order to calculate the community structure of the network accurately and quickly, it is necessary to use the appropriate algorithm.

FN algorithm is a kind of agglomeration algorithm to divide the communities of the network. It has the advantage of fast computing and the ability to divide networks with multiple communities. But it only works on non-weighted networks and needs to be improved.

The basic idea of agglomeration is to think of each node as a community, and then gradually merge the groups until the whole network is merged. In the process of merging, the modularity Q is used as the standard for the quality of the merger. Each merger requires that the modularity Q increase or decrease the minimum. Then, merge all the nodes and look for the maximum of the modularity Q, which means the result of the community division.

The modularity Q can be modified the following form in a weighted network (Eq. 17) (Chen and Xu 2013):

$$Q^w = \sum_{i=1}^{c} ({p^w}_{ii} - (h_i^w)^2) \tag{17}$$

where p_{ii}^w is the proportion of the support capability of the route that connects the nodes of community *i*; h_i^w is the proportion of the support capability of the route that connects the nodes of community *i* from the outside in the network.

The FN algorithm runs as follows:

Step 1: Initialize the network, set each node as an independent community, make the modularity $Q = 0$. Define a symmetric matrix p^w, its element p_{ij}^w, and auxiliary variable a_i^w conform Eq. 18 and Eq. 19:

$$ {p^w}_{ij} = \begin{cases} w_{ij} / 2w, & i \text{ and j are connected} \\ & 0,\text{else} \end{cases} \tag{18}$$

$$ {a^w}_i = \sum_j {p^w}_{ij} \tag{19}$$

where p_{ii}^w is the proportion of the support capability of the route that connects the communities *i* and *j* to the total support capability of ATMTSS; *w* is the sum of support capability, and a_i^w is the sum of the elements in the diagonal of the matrix p^w.

Step 2: Merge connected communities sequentially and calculate the incremental modularity (Eq. 20):

$$\Delta Q^w = {p^w}_{ij} + {p^w}_{ji} - 2{a^w}_i {a^w}_j = 2({p^w}_{ij} - {a^w}_i {a^w}_j) = \frac{1}{2w} - \frac{\sum_j w_{ij} \sum_i w_{ij}}{(2w)^2} \tag{20}$$

where w_{ij} is the support capability of the route that connects the communities *i* and *j*.

Make sure that the *Q* increases as large as possible during calculations. And then update the value of Q^w. $Q^w = Q^w + max(\Delta Q^w)$.

Step 3: Repeat Step 2, merging the community until the whole network is merged into a whole community. The maximum Q^w corresponds to the best community structure results.

We can use this improved FN (IFN) algorithm to detect the community structure of the ATMTSS network.

RESULTS AND DISCUSSION

In this section, the ATMTSS network in Southwest China is selected to establish a network topology model, using the complex network analysis method to calculate the number of nodes, degree, degree distribution, node strength, node strength distribution, clustering coefficient, average path length, and network metrics. Also, the IFN algorithm is used to study the community structure of the network.

ATMTSS NETWORK MODEL

It was used the model construction principle mentioned before to construct the ATMTSS network model in Southwest China. The region has 56 nodes, 9 route radar control systems, 7 route VHF communication systems, and 17 sectors. There are 14 sectors left after merging the sectors with different levels of elevation in the same places. The initial non-weighted topology network is shown in Fig. 3. In order to obtain the weighted ATMTSS network model, the network edge should be weighted according to the equipment support capability. When assigning weights to edges in the network, the coverage of PSR/SSR and VHF in this area should be confirmed, as shown in Fig. 4 and Fig. 5. According to the coverage of the devices and the distance of the routes, weighted network is obtained.

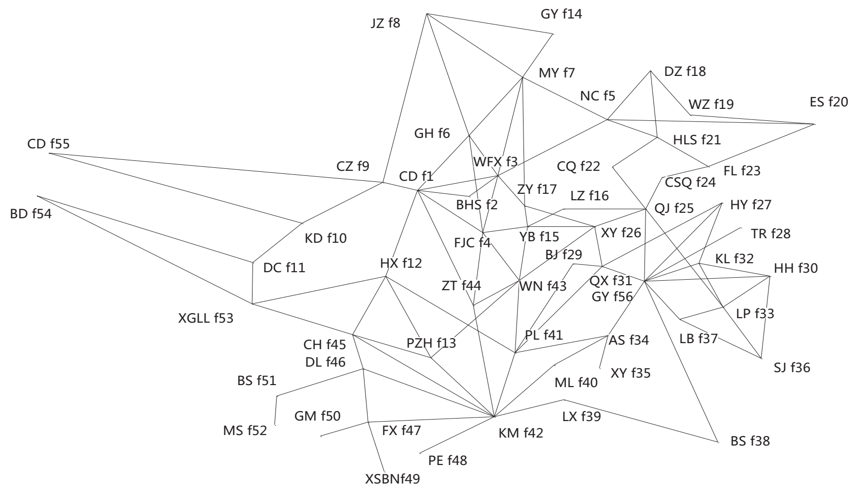


Figure 3. Air Traffic Management Technical Support System (ATMTSS) network topology model.

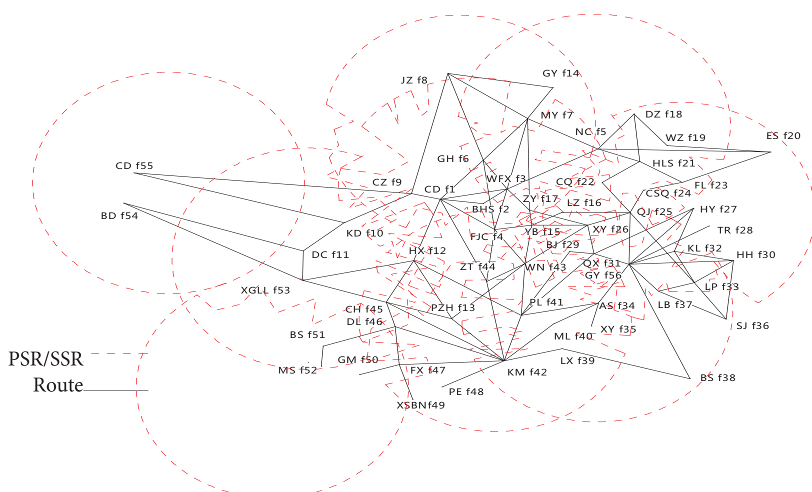


Figure 4. Primary Surveillance Radar/Secondary Surveillance Radar (PSR/SSR) coverage in Southwest China.

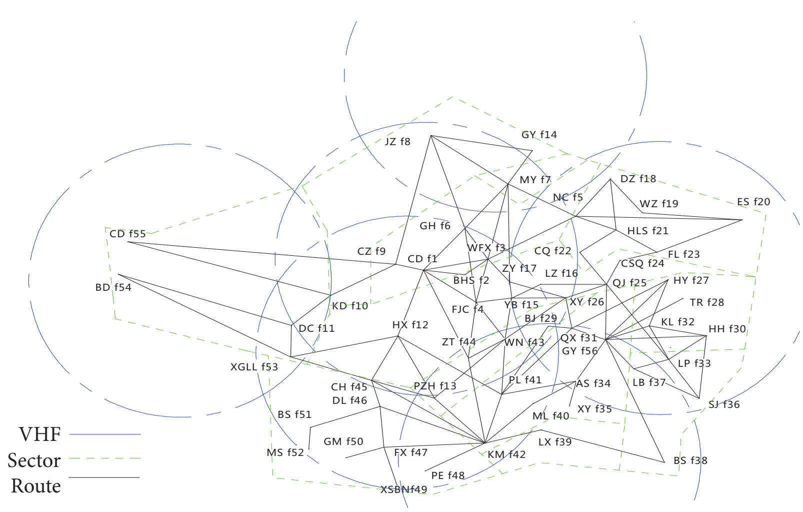


Figure 5. Very High Frequency (VHF) and sector coverage in Southwest China.

ATMTSS NETWORK STATISTICAL CHARACTERISTICS

In order to fully analyze the structure and function of the network, the measurement indexes of the network are applied to the ATMTSS network in the Southwest region. First, the non-weighted and weighted indexes are used to analyze the statistical characteristics of the ATMTSS network, and the results are as follows:

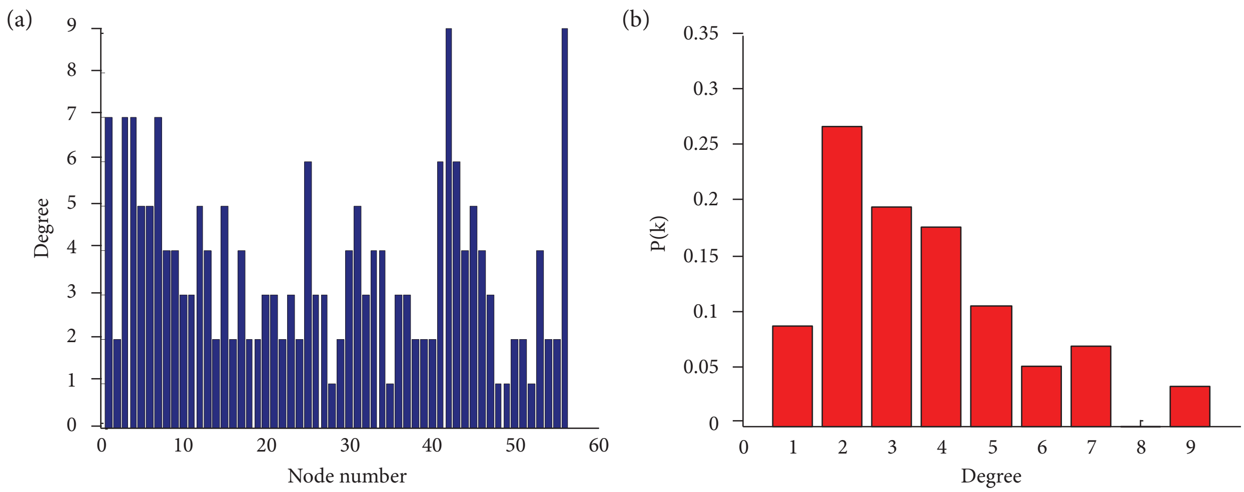


Figure 6. Degree and degree distribution. (a) Degree of each node; (b) degree probability distribution.

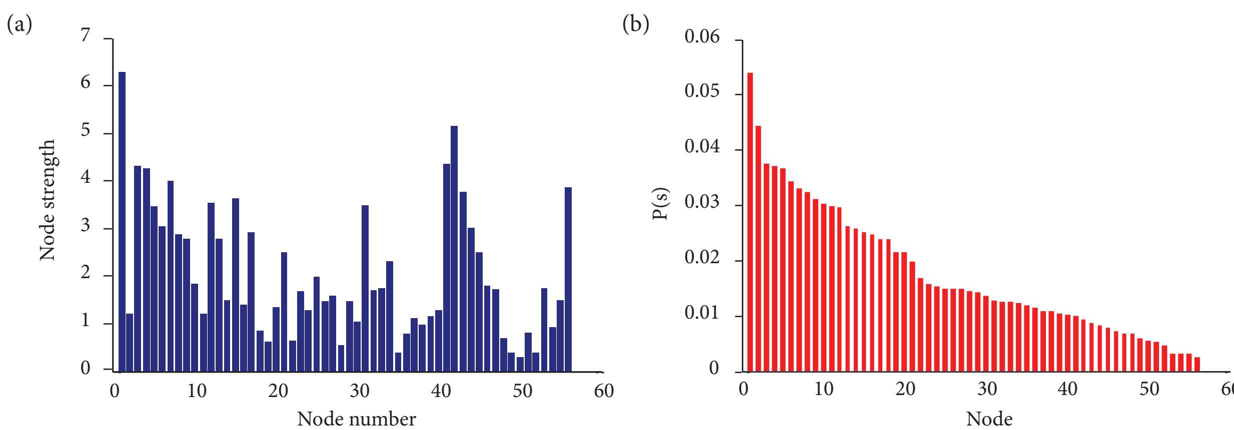


Figure 7. Node strength and node strength distribution. (a) Node strength of each node; (b) node strength probability distribution.

Table 1. Air Traffic Management Technical Support System (ATMTSS) network characteristics.

Area	Node number	Average degree	Clustering coefficient	Weighted clustering coefficient	Average path length	Network diameter
Southwest	56	3.6071	0.2566	0.2308	3.7786	9

The node names in the ATMTSS network in Southwest China are abbreviations of real cities, where CD f1, CQ f22, KM f42, and GY f56 are the provincial capitals of four provinces in Southwest China. They are most economically developed cities in this region.

Fig. 6 (a) shows that the degrees of most nodes in the ATMTSS network range from 2 to 4, while CQ f42 and GY f56 have the largest degree value (9), followed by CD f1, WFX f3 etc., with degree value of 7. But Fig. 7 (a) shows that CD f1 has the largest node strength in Southwest region, while the node strength of CQ f42 is in the second place. The reason is that CQ f42 and

GY f56 are mountainous areas, which requires a large number of airlines to ensure the smooth traffic. Moreover, CD f1 is the center city in the Southwest region, and it needs strong support capability.

Fig. 6 (b) shows that nodes with degree ranging from 2 to 6 obey power-low distribution, while Fig. 7 (b) shows that node strength in the Southwest China obey power-low distribution better than degree distribution. The reasons are that most nodes do not require a large number of routes and strong support capability to ensure smooth traffic flow.

Table 1 shows that there are 56 nodes in this network and each point is connected to 3.6 points on average. This is consistent with the degree distribution. Moreover, the clustering coefficient of ATMTSS network is low, while the weighted clustering coefficient is even lower. The reasons are that ATMTSS devices need to be evenly distributed to ensure the balance of air traffic development and the air traffic security in Southwest China. In addition, the average path shows that an aircraft needs to go through 3.7786 edges to reach another node, while the network diameter is 9; the reason is that the ATMTSS network is a complex network with small-world characteristic.

ATMTSS NETWORK COMMUNITY STRUCTURE

In order to analyze the performance of the ATMTSS network, the IFN algorithm in Section 4 is used to divide the community structure of the network. Through the results of community division, we can understand the development of the system and the key areas. The results are shown in Fig. 8 and Fig. 9.

Fig. 8 shows that the maximum Q of non-weighted ATMTSS network is 0.5603 in the 51th calculation, while it is 0.5693 in weighted ATMTSS network by calculating 50 times. We get the calculation results of two networks and reverse the calculation process as Fig. 9 shown. Then we cut the Fig. 9 along the lines to get the node numbers of each community structure. The results of community structure detection are shown in Fig. 10.

Fig. 10 (a) shows that there are five community structures in ATMTSS network. The five communities divide the Southwest into five regions. Each region has a relatively developed city: CD f1, CQ f22, KM f42, and GY f56 are the capitals of the four Southwestern provinces, while WN f43 is the largest autonomous county in the Southwest region. So, the reason for the formation of community structure in the ATMTSS network is the economic impact of these cities.

Fig. 10 (b) shows that there are six community structures in weighted ATMTSS network. CZ f9, KD f10, and CD f55 are separated from the economic impact of CD f1. The rest of the community structure is also divided differently from the previous one. This is because the support capability in the edges becomes another factor to consider, not just the connectivity situation. The support capability is less affected by developed cities as much as the economy. And it is more affected by the geographical location of the devices. The support capacity of remote areas is greatly affected by geographical location factors, which leads to the weak support capability of routes between the developed areas and the remote areas. Therefore, remote areas are separated from the community structure of the developed areas to become independent communities.

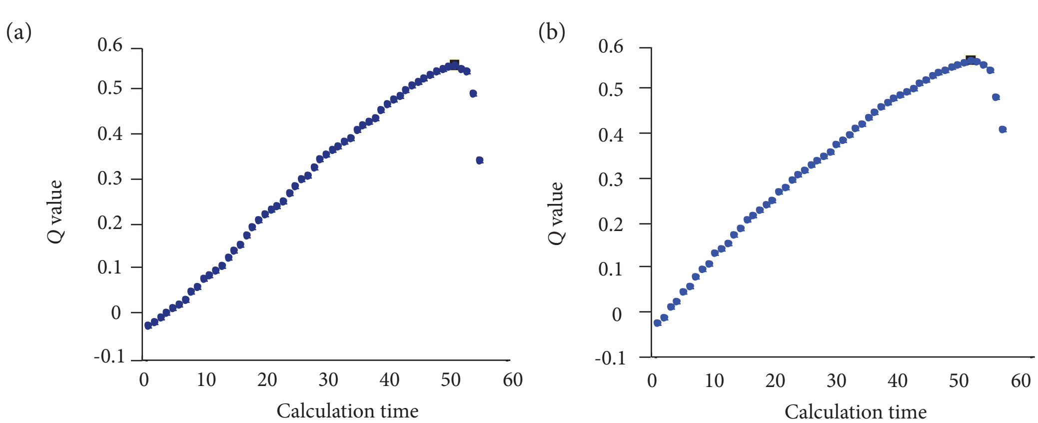
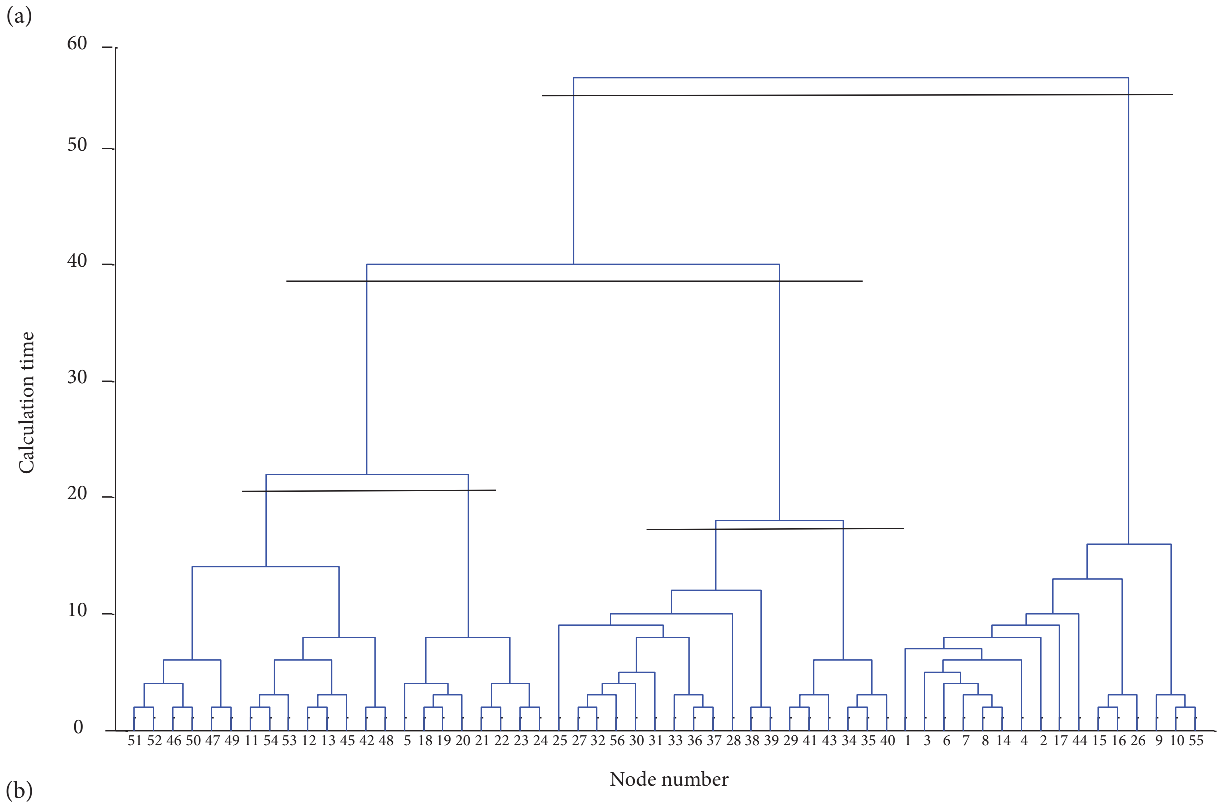


Figure 8. Q in each calculation. (a) Q in non-weighted ATMTSS network; (b) Q in weighted ATMTSS network. ATMTSS = Air Traffic Management Technical Support System.



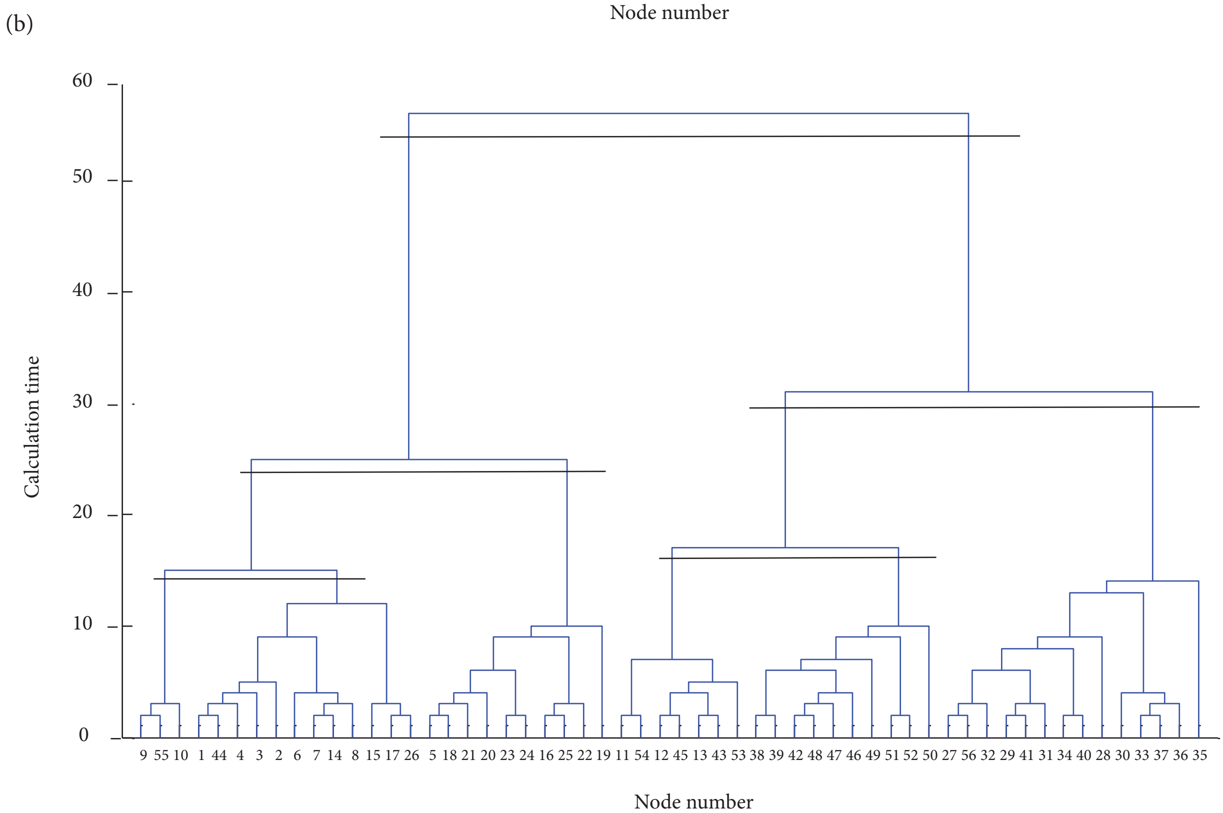


Figure 9. Calculation results. (a) Calculation result in non-weighted ATMTSS network; (b) calculation result in weighted ATMTSS network. ATMTSS = Air Traffic Management Technical Support System.

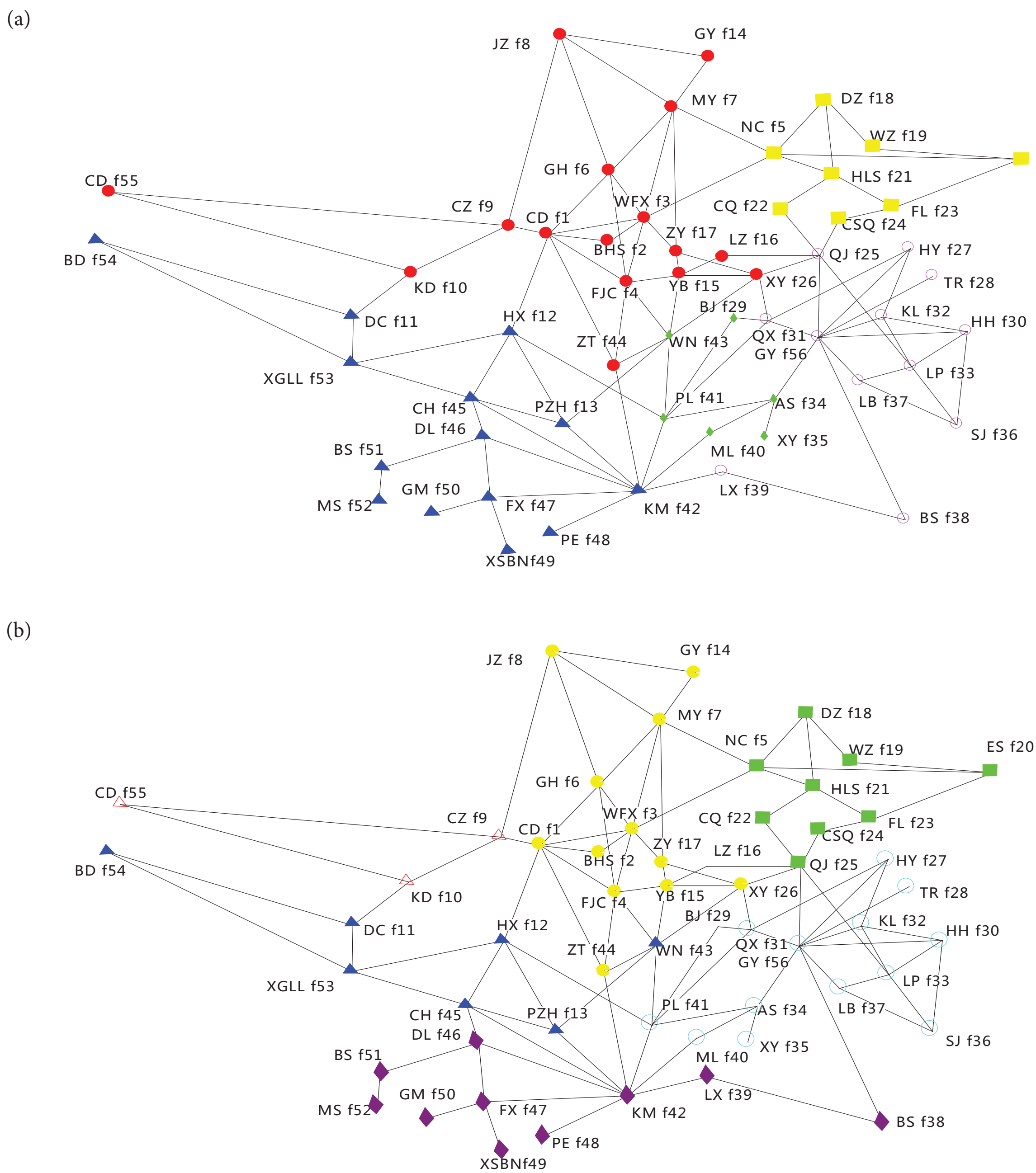


Figure 10. Community structure results. (a) Community structure in non-weighted ATMTSS network; (b) community structure in weighted ATMTSS network. ATMTSS = Air Traffic Management Technical Support System.

CONCLUSIONS

In order to make reasonable suggestions for the expansion of ATMTSS, a method of analyzing ATMTSS based on complex network theory is proposed in this paper. The ATMTSS is constructed into a weighted complex network using graph theory, and the working characteristics and geographical location of the system equipment are fully considered. Then the network is analyzed by both non-weighted and weighted statistical characteristics indexes and the community structure. And the algorithm of non-weighted community structure is improved so that it can be successfully applied to weighted networks.

The ATMTSS of Southwest China was selected, and the network construction and performance analysis were carried out. The results of the analysis are as follows:

The ATMTSS network in Southwest China is a complex network with low clustering coefficient and small-world and random characteristics. The four provincial capitals of Southwest China (CD f1, CQ f22, KM f42, and GY f56) have the leading degree and node strength in the whole region.

It shows that the construction of ATMTSS is centered on the economically developed cities and that these cities have the highest number of routes and the sum of the highest supporting capacity.

The result of the community structure with non-weighted network also supports the result of the statistical characteristics. Communities of non-weighted network are also centered in economically developed areas.

But the results are different from the previous ones if the network is divided according to the guarantee ability. Remote nodes in the Northwest and Southwest areas of the region are divided into two new communities.

Because these areas are too far away from economically developed areas, their air traffic cannot be integrated with them and can only be supported independently. When the function of the devices on a route in a remote area is impaired, it is difficult to receive support from other regions, thereby endangering the safety of air traffic in this area.

As a result, the expansion of the ATMTSS system requires additional air traffic support in remote areas.

AUTHOR'S CONTRIBUTION

Conceptualization, Fan K and Han S; Methodology, Fan K; Investigation, Fan K; Yu L and Quan J; Writing – Original Draft, Fan K; Writing – Review & Editing, Fan K; Han S and Li W; Resources, Yu L; Quan J and Li P; Supervision, Han S.

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