Influential Node Ranking and Invulnerability of Air Traffic Cyber Physical System

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Abstract: To ensure flight safety, the complex network method is used to study the influence and invulnerability of air traffic cyber physical system (CPS) nodes. According to the rules of air traffic management, the logical coupling relationship between routes and sectors is analyzed, an air traffic CPS network model is constructed, and the indicators of node influence and invulnerability are established. The K-shell algorithm is improved to identify node influence, and the invulnerability is analyzed under random and selective attacks. Taking Airspace in Eastern China as an example, its influential nodes are sorted by degree, namely, K-shell, the improved K-shell (IKS) and betweenness centrality. The invulnerability of air traffic CPS under different attacks is analyzed. Results show that IKS can effectively identify the influential nodes in the air traffic CPS network, and IKS and betweenness centrality are the two key indicators that affect the invulnerability of air traffic CPS.

Key words: complex network; air traffic cyber physical system; improved K-shell algorithm; influential node ranking; invulnerability

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0 Introduction

In recent years, the rapid development of the air transport industry has increasingly worsened the problem of flight delays, which has not only affected the economic benefits of aviation but also imposed hidden safety risks. On May 19, 2016, a computer failure caused a temporary closure of the airspace in Stockholm, Sweden. As a consequence, airplanes from the local airport failed to take off on time. On August 10, 2019, 3 023 flights were canceled in Eastern China due to typhoon "Lichma". It can be seen that when an emergency, such as equipment failure or adverse weather, causes air traffic control (ATC) positions or waypoints to fail, the entire air traffic system would not be able to operate normally. Therefore, alleviating flight delays and promoting high-quality development of civil aviation have become a major issue in the future.

Air traffic management, as a highly complex task, is of great importance to the overall order and safety of the air traffic system[1]. The air traffic management system integrates the communication network and physical environment to realize the functions of controlling and directing flights, which is characterized by a typical cyber physical system (CPS). The deep integration of the network and environment forms a multi-dimensional heterogeneous complex system that can achieve real-time sense, dynamic control as well as information service. This system gradually evolves into a physical air traffic information system (air traffic CPS) with frequent interaction of traffic flow and information flow. In this study, an air traffic CPS model is constructed. Its influential nodes are identified and the invulnerability is analyzed. We provide insight into the safe operation of the air traffic management system.

In recent years, the identification of key nodes

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in aeronautical complex networks has attracted general interest. In 2014, Lordan et al.[2] used a media-centric adaptive strategy to identify the key airport nodes in global aviation networks. In 2017, Pan et al.[3] evaluated the key nodes in the ATC navigation network and sorted the importance of navigation equipment of Chengdu control area in the southwest. In 2018, Wen et al.[4] proposed an aviation network node importance evaluation method based on the improved node deletion method and proved that potential key-airports in China and America can be discovered by the method. The studies above have analyzed the network characteristics from the aspects of airports, routes and sectors in the air traffic network, but have not taken into account the integrity of air traffic systems or the relationship between systems.

This problem has been addressed in some literature. In 2013, Sampigethaya et al.[5] proposed a novel CPS framework to understand the cyber layer and cyber-physical interactions in aviation to study their impacts on each other. In 2016, Roy et al.[6] established an evaluation model based on CPS to analyze the degree of threat to the air traffic management system caused by the interruption of the information network under attack. In 2017, Ren et al.[7] described how flight operations control (FOC) and air navigation service provider (ANSP) in the aviation system transit to CPS in detail. Although these studies have laid the foundation for future research on air traffic CPS, they have only offered a simple description of the aviation system from the perspective of CPS, while the unified modeling theory has not been proposed so far.

Destruction of a few influential nodes is likely to cause the entire network to fail. Studies have shown that such destruction in power grid CPS can paralyze the entire power system[8]. For air traffic CPS, adverse weather, severe epidemics, military activities, equipment failures, and other events may lead to the closure of the sectors managed by failed ATC positions or congestion of waypoints. Consequently, the air traffic CPS information network cannot operate smoothly, thus inducing extensive flight delays and safety hazards.

In this paper, the complex network theory is used to build an air traffic CPC model. The interaction between cyber and physical systems is described scientifically and reasonably, and the nodes in the air traffic CPS are sorted to identify the influential nodes. Different strategies are used to attack the network to analyze its invulnerability. The results provide a theoretical basis for the future scientific management of air traffic and can improve air traffic operation safety.

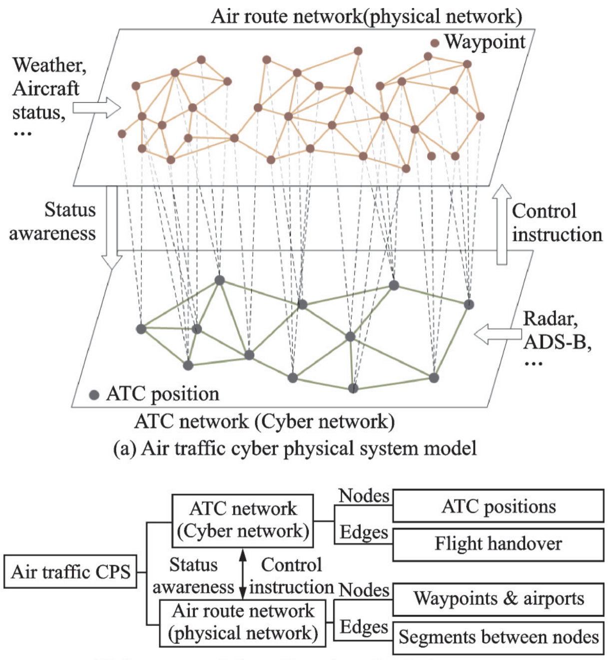
1 Air Traffic CPS Model

It is proved that CPS can model systems with coupled relationships[9]. The rising complex network theory also provides an approach to studying structural functions of coupled networks.

In this paper, the topological abstraction of the air traffic CPS is obtained based on complex network theory. An air traffic CPS network model is established combining the current air traffic management rules[10] and the logical connection between air route and ATC sectors, as shown in Fig.1. The air traffic CPS network consists of two interactive and mutual-influencing parts: The physical network, which is the air route network, and the cyber network, which is the air traffic control network. Waypoints and ATC positions are abstracted into nodes of the two networks respectively and are linked according to their relationships—ATC positions observe the changes of waypoints status and control the operation of waypoints.

Adjacency matrix $\{\alpha_{ij}\}_{N\times N}$ and $\{\beta_{ij}\}_{N\times N}$ are used to represent the connection of N nodes in ATC network and air route network, respectively. When there is a connected edge between node i and j, $\alpha_{ij}=\alpha_{ji}=1, \beta_{ij}=\beta_{ji}=1$, otherwise, $\alpha_{ij}=\alpha_{ji}=0, \beta_{ij}=\beta_{ji}=0$.

Fig.2 explains the coupling relationship between ATC network and air route network. Air traffic controllers and pilots consider aircraft as physical entities, and air traffic information perception and communication control are deeply integrated



(b) Structure of air traffic cyber physical system

Fig.1 Air traffic CPS

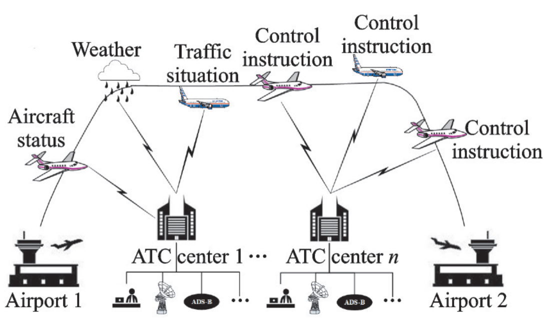


Fig.2 Coupling relationship of air traffic CPS

through controller-pilot data link communication (CPDLC). Air traffic controllers receive information such as the aircraft status, the traffic situation, the weather conditions, and the information sensed by radar, ADS-B, weather monitoring station or other equipment from the ATC center. Controllers analyze and process the information and issue control instructions to pilots. Pilots give feedback to the corresponding control instructions, change the aircraft state, therefore enable to smooth traffic flow.

1.1 Physical network

The physical network of air traffic CPS is the air route network, scilicet the traffic flow network. Waypoints (compulsory reporting points and navigation stations) and airports in the airspace sector controlled by each ATC position are considered as nodes. If the navigation station and the airport are at the same position, only keep the airport and use the segment between nodes as the edge. The function of the air traffic system is to ensure the safe and efficient operation of air traffic. The process is mainly implemented in the air route network. To facilitate research, the following procedures are performed.

(1) The physical network is undirected, and for those parallel routes, only one direction is reserved.

(2) Delete waypoints that do not change the route direction or connection.

(3) When constructing the air route network, the pilot and aircraft are considered as a unified whole.

(4) Neglect temporary and international air routes, and delete the isolated border points.

1.2 Cyber network

The air traffic CPS cyber system is the ATC network with ATC positions as nodes and flight handover relations as edges. The aircraft reports its current operating status to the corresponding ATC positions in the air route network and follows the instructions given by the ATC positions[11]. For convenience, this research makes the following assumptions.

(1) Merge the high and low sectors in the airspace, and each ATC position is responsible only for the flight handover of the corresponding sector.

(2) The information network is undirected.

(3) When constructing the air traffic control network, the ATC position and the sector controlled by it are considered as a unified whole.

2 Indicators of Air Traffic CPS Model

Evaluating node influence is vital for improving the invulnerability of complex networks[12]. Identifying and sorting influential nodes in air traffic CPS provide a basis for attack simulation in the later invulnerability research. Protecting critical nodes and their connected edges prevents the network from losing its robustness in case of damage[13], which helps to manage sectors scientifically and alleviate air traffic congestion. The performance of the CPS is closely bound up with the nodes that provide various services for the whole system[14]. Studying the invulnerability of the air traffic CPS, observing the node characteristics with poor invulnerability and protecting the sectors where the node is located can effectively avoid continuous attacks on the same node, and reduce losses through traffic flow prediction and control sectors. To analyze the node influence and CPS network invulnerability better, the indicators of influence and invulnerability are defined in this paper.

2.1 Characteristic indicators of node influence

Node influence refers to the ability of a node to directly or indirectly affect the network structure or other nodes in the air traffic CPS network. The quantitative description of the node influence in the network helps us better analyze the network characteristics. However, many factors need to be considered such as the attributes of the nodes themselves and the influence of the connecting edges between nodes[15]. The definitions and symbols of the characteristic indicators of node influence are shown in Table 1.

Table 1 Indicators of air traffic CPS

Indicator	Symbol	Definition
K-shell level	$k_s(i)$	$k_s(i)$ indicates the level at which node i is decomposed by K-shell. The higher the level is, the greater the influence is.
Degree	k_i	k_i is the number of nodes adjacent to node i, and nodes with high degree are more influential. Node with many neighboring nodes has a large spread of information flow and traffic flow too.
Betweenness	$B(i)=\sum_{s\neq t}\frac{n_{st}(i)}{n_{st}}$	n_{st} represents the number of shortest paths connecting node s and node t; $n_{st}(i)$ the number of shortest paths that connect node s and t and pass through node i. The larger the betweenness is, the stronger the intermediary of the node is and the greater its external influence is.
Edge weight	$\omega_{ij}=k_i+k_j$	k_i and k_j represent the degrees of nodes i and j, respectively. Large ω_{ij} means that the information flow or traffic flow can spread to more nodes.
Edge influence coefficient	$\gamma_{ij}=\frac{(N_i\cap N_j)+1}{(N_i\cup N_j)+1}$	N_i and N_j represent the set of adjacent nodes of nodes i and j, respectively. $N_i\cap N_j$ represents the intersection of the adjacent nodes of nodes i and j, which is the overlapping portions of adjacent nodes. $N_i\cup N_j$ is the sum of the adjacent nodes of nodes i and j (excluding i and j), plus 1 to both the numerator and the denominator to avoid the case that the influence coefficient becomes 0.
Node weight	$S_i=\sum_{j\subset N_i}\gamma_{ij}\cdot k_s(j)+\sum_{j\subset N_i}\omega_{ij}$	S_i represents the sum of edge weights and influence of all nodes adjacent to i, where the influence of adjacent nodes is defined as the product of the edge coefficient γ_{ij} and the K-shell level $k_s(j)$.

In the previous research on unweighted networks, the connected edges between nodes were mostly regarded to have the same influence, but if two respect nodes are connected to many nodes, the information flow or traffic flow spreads more widely between the two nodes, and the connecting edge between the two nodes is more influential. Therefore, we use flow as edge weight to represent the influence of edges. At the same time, node weight is taken into consideration, and the edge influence coefficient is established as the parameter for identifying the influence of the edge. Next, the original K-shell algorithm is used to obtain the node's K-shell level, and edge weights and edge influence coefficients are combined to obtain node weight. The greater the node weight is, the greater the influence is. The improved K-shell (IKS) remedies the defect that the original K-shell algorithm cannot accurately measure the influence of nodes when there are many identical values as they will be judged to have the same influence[16], therefore it functions better in ranking influential nodes. The calculation process is shown in Fig.3.

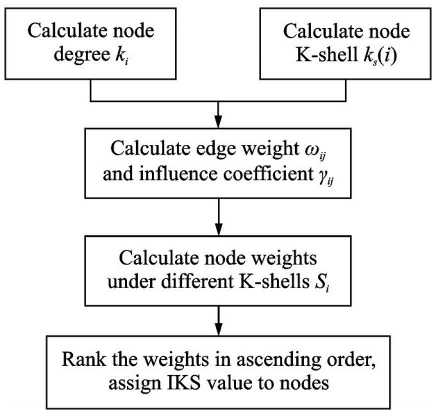


Fig.3 Flow chart of IKS

In this paper, the degree of air traffic CPS and the K-shell level of the nodes are calculated, and the edge weights and edge influence coefficients are calculated afterward to get the node weights so that the nodes can be sorted accordingly.

2.2 Characteristic indicators of invulnerability

Invulnerability refers to the characteristics of a network to maintain and restore its functions to a certain degree when its structure is damaged[17]. During operation, if the air traffic CPS is affected by adverse weather, major epidemics, military activities, equipment failure or other events, its invulnerability will drop to a certain value, some nodes and their connected edges will fail, the network will get damaged or even break down, and ATC operations would not be able to carry out normally either. This will lead to large-scale air route congestion and flight delays. Once a flight delay occurs, it will disrupt the original parking stand allocation, runway scheduling, and the order of flight arrivals and departures. Various tasks affect each other, thereby increasing the complexity of civil aviation resource scheduling and resulting in huge civil aviation security risk in the end. Besides, flight delays will detain a large number of stranded passengers at the airport, which will affect security and control of the airport.

To study the invulnerability, attacks on the network are simulated. For showing strong uncertainty, adverse weather, equipment failure and other effects are considered as random attacks. While the damages caused by communication failure resulting from military activities or terrorist attacks are relatively subjective, so they are considered as selective attacks.

Network efficiency and the relative value of the maximum connected subgraph are used to evaluate the structural damage of the air traffic CPS. The definitions and symbols of these indicators are shown in Table 2.

The coupling invulnerability of the air traffic CPS network is studied according to the coupling relationship between the air traffic control network and air route network. The simulation attack, as shown in Fig.4, consists of four steps.

Table 2 Indicators of invulnerability of air traffic CPS

Indicator	Symbol	Definition
Network efficiency	$E=\dfrac{2}{M(M-1)}\sum_{i>j}\dfrac{1}{l_{ij}}$	M indicates the number of connected ATC positions in the ATC network and the number of connected waypoints in the air route network. l_{ij} is the shortest distance between node i and j. When node i and j are not connected, $l_{ij}=\infty$. The closer E is to 1, the greater the network efficiency becomes.
Relative value of the maximum connected subgraph	$G=\dfrac{g'}{g}$	g represents the number of nodes in the ATC network or air route network before attack. g' represents the number of nodes in the maximum connected subgraph of the ATC network or air route network after attack.

Step 1 Choose the ATC positions in the air traffic CPS network for invulnerability research. The coupling failure rule of the ATC network and the air route network is set as follows. ATC positions in the ATC network cannot transmit information when failed. When all the corresponding waypoints become invalid, the failed waypoints and their connected air routes are removed. The coupling invulnerability of the air traffic CPS is studied by observing the changes of invulnerability indicators under different attacks.

Step 2 Sort the ATC positions randomly using Python. Then sort the ATC positions in the air traffic CPS network in the descending order by degree, MKS and betweenness centrality.

Step 3 Remove the ATC positions according to the order in Step 2 to simulate attacks on the network. The ATC positions cannot work properly so that the sectors under their management are closed, all the waypoints in the sector become invalidated, and the structure and capacity of the air route network are also severely affected. Then the network invulnerability is obtained under degree-first, IKS-first and betweenness-centrality-first attacks.

Step 4 Observe the changes in invulnerability indicators, network efficiency and relative value of the maximum connected subgraph to analyze the invulnerability of the air traffic CPS and learn about the ability of the control network to maintain its structure after attack.

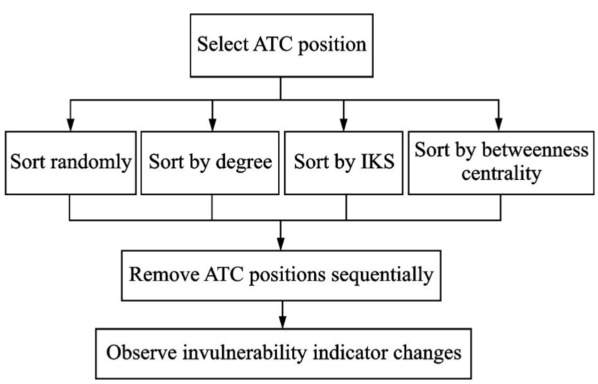


Fig.4 Flow chart of attack simulation on the network

3 Empirical Analysis

The airspace under the jurisdiction of the Eastern China Air Traffic Management Bureau, one of the busiest airspaces in China, is used to establish the Eastern China Air Traffic CPS model. The actual radar and ADS-B data are processed based on TrackDig (a three-dimensional high-speed flight data mining software) to restore the track in the map. Then the geographic coordinates of sectors and waypoints corresponding to each ATC position in Eastern China are imported into ArcGIS (a geographic information system software) to finish the mapping. The information layer (air traffic control network), as shown in Fig.5(a), is made up of 33 ATC positions as nodes and 69 edges. The physical layer (air route network) has 171 waypoints and 261 air routes, as shown in Fig.5 (b).

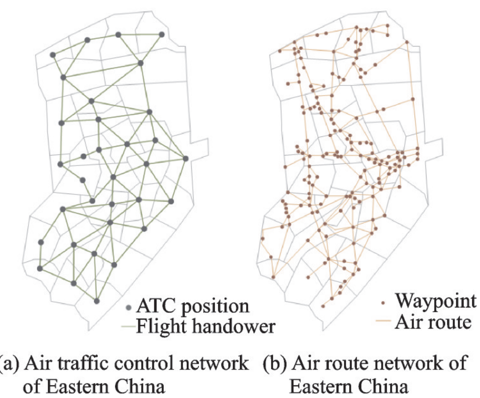


Fig.5 Air traffic CPS network of Eastern China

3.1 Ranking and analysis of influential nodes in air traffic control network

Based on the traffic statistics of the airspace under the jurisdiction of the Eastern China Air Traffic Management Bureau of China, the ATC positions of the control network are calculated using the IKS algorithm to obtain the weighted influence of each ATC position. Great influence means that this ATC position has flight transfer relationship with many adjacent positions. The top 15 IKS nodes of the air traffic control network are taken as examples, and sorted from large to small by IKS, degree, K-shell and betweenness centrality. The sorting result is shown in Table 3.

Through comparison, it can be seen that some of the top 10 ATC positions are the same among the sorting results identified by different methods. The

Table 3 Top 15 influential nodes in the air traffic control network of Eastern China

Node	IKS	K-shell	Degree	Betweenness centrality
Shanghai 19	29	3	7	0.175 5
Shanghai 02	28	3	6	0.141 8
Shanghai 04	27	3	6	0.151 6
Shanghai 05	26	3	6	0.093 0
Shanghai 15	25	3	6	0.211 8
Shanghai 07	24	3	6	0.224 1
Shanghai 01	23	3	5	0.090 2
Shanghai 16	22	3	5	0.064 4
Shanghai 06	21	3	5	0.077 5
Shanghai 09	20	3	5	0.031 6
Shanghai 20	19	3	5	0.083 3
Shanghai 12	18	3	5	0.139 9
Shanghai 24	17	3	4	0.015 1
Shanghai 18	16	3	4	0.075 6
Shanghai 03	15	3	4	0.103 2

ATC positions with great influence according to the IKS algorithm are also at the highest level of the K-shell algorithm, and the top 10 ATC positions are highly consistent with those ranked by degree. This result further illustrates the effectiveness of IKS. Also, No.19 ATC position has the most influence according to all the methods except closeness centrality. It can be seen that there is information transmission between No. 19 ATC position and many other surrounding positions. This means that No.19 ATC position has an impact on its surrounding positions, and it is the central hub of the air traffic CPS throughout Eastern China.

3.2 Ranking and analysis of influential nodes in air route network

As a scale-free network[18], the air route network has severe heterogeneity in the connection between nodes. The typical feature is that most waypoints in the network are connected to only a few nodes, and there are only a few waypoints connected to a large number of nodes. Generally speaking, there is a distribution relation of traffic flow between this kind of node and other surrounding waypoints, which has a greater influence on the surrounding area. Ordinary influence recognition methods can also identify these waypoints, but it is difficult to distinguish the influence of most nodes in the air route network. To prove the effectiveness of the IKS algorithm, the node influence of the airway network is also calculated. The top 15 IKS nodes in the air route network are taken as examples, sorted from large to small, and compared with other algorithms, as shown in Table 4.

Table 4 Top 15 influential nodes in the air route network of Eastern China

Node	IKS	K-shell	Degree	Betweenness centrality
Yunhe	114	3	7	0.086 1
Jiuting	113	2	7	0.142 9
Luogang	112	2	6	0.189 3
Lishui	111	2	6	0.229 3
UGAGO	110	3	5	0.028 8
Pudong	109	2	5	0.083 2
Jingdezhen	108	2	6	0.112 7
Pixian	107	2	5	0.092 9
Lianjiang	106	2	5	0.039 7
Lishe	105	2	5	0.081 1
SASAN	104	2	5	0.035 5
PIMOL	103	2	5	0.026 7
Nanxiang	102	2	5	0.034 7
Fuqing	101	2	5	0.018 3
EKIMU	100	2	4	0.021 7

The comparison in Table 4 shows that IKS has a significant effect on identifying the influence nodes of the Eastern China Air Traffic CPS route network. A total of 171 waypoints are divided into 114 layers sorted by IKS, and the influence of most nodes in the network can be identified. In the air route network, the sorting of the top 10 influential nodes is highly close to the result of degree. Although the influential nodes are in the second and the third layers of the original K-shell algorithm, the highest level of the original K-shell algorithm after decomposition is only three because the connections between air route network nodes are not dense. This result also shows that this method cannot effectively distinguish the influence of scale-free networks with many nodes. Different from the identification of influential nodes in the air traffic control network, the centrality of the air route network differs greatly from the IKS sorting. This is because the betweenness centrality describes the influence of the ability of the node itself as an intermediary. Another reason is that the connectivity between waypoints is relatively poor, so most nodes cannot play an intermediary role. Consequently, the results are not accurate.

3.3 Invulnerability analysis of air traffic CPS

According to the coupling relationship of the two layers of air traffic CPS network, when the ATC network is affected, the ATC positions cannot function properly which leads to the closure of sectors, and therefore the waypoints inside fail and the structure of air route network are changed. We learn how air traffic CPS works by attacking the nodes in air traffic control network and observing the changes in air route network.

The specific relationship between ATC sectors and the waypoints under their control is described in Table 5.

Table 5 Waypoints controlled by different ATC positions

ACT position	Waypoint
Shanghai 01	Quzhou, Yiwu, Tonglu, ABVIL, UGAGO, ELNEX
Shanghai 02	Andong, SUPAR, Lishe, Shengzhou
Shanghai 03	SURAK, AKARA, TONIX, BOLEX, BONGI, DUMET
Shanghai 04	Yangzhou, Nantong, Changzhou, SASAN, PIMOL, XUTGU, UNTAN, PIKAS, XIREM
Shanghai 05	MATNU, ALDAP, PINOT, IPRAG, NINAS, LASAN, ELAGO, ATRIP, DADAT, Shuyuan, Pudong, Hengsha, Jiuting, Hongqiao, Nanxiang, EKIMU, POMOK, Wuxi
⋮	⋮

Thirty-three ATC positions are sorted by the degree, IKS, betweenness centrality and in random, then removed in turn to simulate degree-first, IKS-first, and betweenness-centrality-first and random attacks on the network. The waypoints controlled by failed ATC positions are removed as well. Therefore, the structure of air route network is changed. Fig.6 shows the comparison of the invulnerability indicators of the air route network of Eastern China Air Traffic CPS using four attack methods. When the top seven ATC positions are attacked, the two indicators, network efficiency and the relative value of the maximum connected subgraphs, decline at a similar speed. If continuing to attack other ATC positions, there is sufficient evidence to show that random attacks have less damage to the air route network than other attack methods. This is because the Eastern China Air Traffic CPS network has better invulnerability against random attacks than selective attacks. From Fig.6(b), it can be seen that air route network collapses fastest under the betweenness-centrality-first attack. Combining Figs.6(a) and (b), it is clear that when No. 11 ATC position fails, the two invulnerability indicators of the air route network hardly change and gradually approach the lowest value, which means the betweenness centrality has most impact on the invulnerability of air route networks.

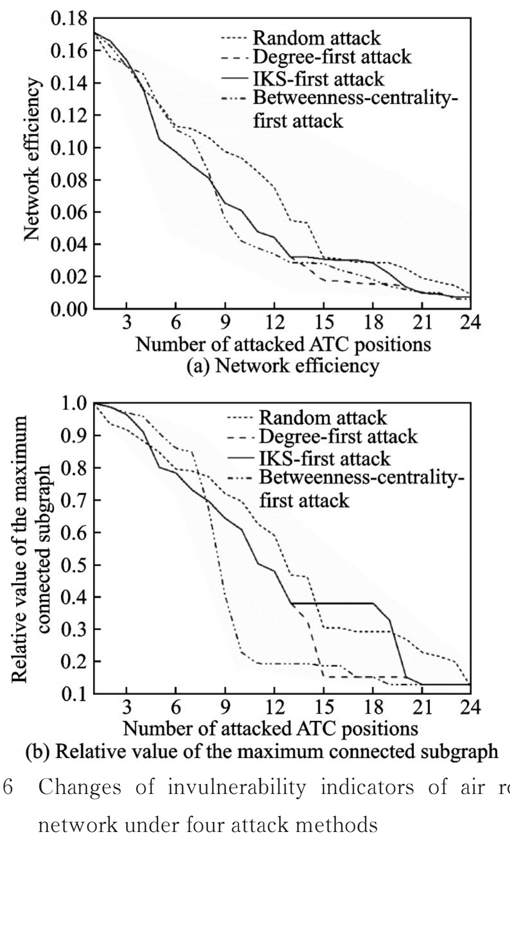


Fig.6 Changes of invulnerability indicators of air route network under four attack methods

ATC positions with greater IKS have greater degrees too. Therefore, given a similar sorting, the invulnerabilities of the air route network are similar at the onset of IKS-first attack and degree-first attack. The difference between IKS-first and degree-first attack is that the two indicators of ATC positions under IKS-first attack reach a stable level first, and then decline, while the indicators under degree-first attack change in the opposite way.

In a nutshell, the air traffic CPS network has the best invulnerability under random attacks, and the invulnerability under selective attacks is poor. The invulnerability indicators of the ATC network fluctuate sharply under IKS-first attack. The structure and traffic capacity of the air route network get damaged fastest under betweenness-centrality-first attack. In conclusion, IKS and betweenness centrality are two important indicators that affect network invulnerability.

4 Conclusions

(1) Air traffic CPS network is a multi-dimensional and heterogeneous complex network integrating the air route network and air traffic control network. This paper builds an air traffic CPS network model and proposes characteristics indicators of node influence and invulnerability, thus providing a new approach to ensuring the safe operation of the air traffic system.

(2) The IKS algorithm can get more accurate results than other methods in identifying the influence of air traffic CPS nodes. Its effectiveness is verified by the airspace of Eastern China. The greater the influence of the air traffic control network node is, the greater the influence of waypoints in the relevant sectors for the ATC position is.

(3) Different attack strategies are used to analyze and study the invulnerability of air traffic CPS network. The results show that the invulnerability is better under random attacks than that under selective attacks. Also, the invulnerability indicators of the air route network fluctuate sharply when the network is attacked according to the IKS sorting order, and the traffic capacity of the air route network decreases fastest when the selective attack is performed according to the betweenness centrality.

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空中交通网络物理系统影响力节点排序与抗毁性研究

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摘要：为了确保飞行安全，采用复杂网络方法研究了空中交通网络物理系统（Cyber physical system，CPS）节点的影响和抗毁性。根据空中交通管理规则，分析了航路与管制扇区之间的逻辑耦合关系，构建了空中交通CPS网络模型，并建立了节点影响力指标和抗毁性指标。改进了K-shell（Improved K-shell，IKS）算法，对网络节点的影响力进行了计算和排序，并分析了随机和选择性攻击下的网络抗毁性。以华东地区空域为例，建立空中交通CPS模型，利用度、IKS和接近中心性对信息网和物理网的影响力节点进行了排序，分析了空中交通CPS在不同攻击方式下的抗毁性。实验结果表明，IKS算法能够有效识别空中交通CPS网络中的影响力节点，改进K-shell和接近中心性是影响空中交通CPS的抗毁性的两个关键指标。

关键词：复杂网络；空中交通网络物理系统；改进K-shell算法；影响力节点排序；抗毁性