Analysis Model of Node Failures and Impact for AANET

Lixia Xie[1](✉), Liping Yan[1], Guangquan Xu[2], and Jiyong Zhang[3]

[1] Civil Aviation University of China, Tianjin 300300, China
lxxie@126.com
[2] Tianjin University, Tianjin 300350, China
[3] Swiss Federal Institute of Technology in Lausanne, 1015 Lausanne, Switzerland

Abstract. To effectively analyze the impact of node failures on the AANET (Aeronautical Ad Hoc Network) and improve the network invulnerability, an analysis model of node failures and impact for AANET is proposed. The main business of AANET is identified and the business network is established based on the business process, the physical network is built according to the real-time AANET, and the business-physical network mapping relationship is used to establish the interdependent networks. Then, the business node volume and network volume are defined and the business node weight is calculated. At the same time, the weight of the physical node is determined by the aggregation degree. Finally, a link survivability calculation module is given and a traffic reallocation strategy based on link survivability is proposed and apply to this model. The experiments show that the model proposed in this paper can accurately analyze the degree of the failure and improve the network invulnerability more effectively than other node failures analysis model.

Keywords: AANET · Node failures · Interdependent networks · Failure propagation model · Link survivability

1 Introduction

AANET is a complex network built on all kinds of aircraft and some base stations, which can cover the business needs of aviation and integrate various communication systems, functional networks, and business systems. On the one hand, the proposal of AANET strengthens the connection between aircraft [1]. On the other hand, it makes the network face more serious node failure risk. Therefore, it is important to analyze the node failures in AANET and propose an optimal network traffic reallocation strategy to improve the network invulnerability.

Jose et al. [2] proposed an effective cascade failure control algorithm based on communication delay but did not concern the communication network coupled with the power grid. Buldyrev et al. [3] proposed a fully dependent dependency network model, in which there is one-to-one correspondence between nodes of two networks. However,

G. Xu et al. (Eds.): FCS 2020, CCIS 1286, pp. 55–64, 2020.
https://doi.org/10.1007/978-981-15-9739-8_5

the one-to-multi relationship between nodes of the two networks is not considered. Wang et al. [4] proposed an improved complex network model for risk assessment of power-communication interdependent networks but did not allocate corresponding weights for different nodes. Zhang [5] proposed that effective evaluation of the importance of nodes could improve the robustness of the network. It also shows that the network can effectively prevent cascading failures in real life if important nodes are protected. Chen [6] proposed a cascading failure model of interdependent networks with different coupling preferences under targeted attack. However, it is not considered that the failed nodes can be restored to working nodes by corresponding means. Han [7] proposed a new cascading failure model with adjustable parameters based on the weighted scale-free network. Peng [8] gave the analysis that affects the security of the information system during the failure process of deliberate attack strategy. But the model lacks consideration about random attacks.

Motivated by those above, in this paper, we propose an analysis model of node failures and impact for AANET. The main contributions of this paper are listed as follows:

a. To describe AANET accurately, we build the business-physical interdependent networks and propose an analysis model that describes the node failures propagation process based on failure propagation model. First, two states of nodes are defined: working node and failed node. Second, the network traffic reallocation mechanism is analyzed. Finally, the failure propagation model is used to obtain the degree of network cascade effect and judge the network destruction degree.
b. Based on a failure propagation model, we propose a traffic reallocation strategy based on link survivability to improve the network invulnerability. First, the link survivability is calculated by combining the node failure rate and distance between nodes. Then, select available optimal links according to link survivability. Finally, the failed node traffic is reallocated by the weight of the neighbor nodes.

The rest of this paper is organized as follows. Section 2 recommends the business-physical interdependent networks building module. In Sect. 3, the node failures analysis model based on failure propagation model is proposed. Section 4 proposes a traffic reallocation strategy based on link survivability. In Sect. 5, the experimental comparisons are carried out and the results are analyzed. Finally, Sect. 6 gives the conclusions.

2 The Business-Physical Interdependent Networks Building Module

In this Section, a two-layer network model is constructed to describe the various business and association relations of the AANET.

2.1 Business Network

Business network G_B is a directed weighted network, expressed as $G_B = (V_B, E_B, W_B)$, where V_B represents the set of business nodes; E_B represents the set of edges, indicating the information interaction between business nodes; W_B represents the set of business node weight, which is determined by the business volume. The following is the calculation process of business node weight W_B:

Define that the network volume is C_B and the total business that the network can handle per unit time is T_B. The business volume of link j is S_j, the shortest path length of the network is $\bar{d}_B$, the shortest path length between node N_u and node N_v is $d_{u,v}$, then:

$$T_B = \sum_{i=1}^{E_B} S_j \tag{1}$$

$$\bar{d}_B = \frac{2}{V_B(V_B - 1)} \sum_{u=1}^{V_B-1} \sum_{v=u+1}^{V_B} d_{u,v} \tag{2}$$

$$C_B = \frac{T_B}{d_B} = \frac{\sum_{j=1}^{E_B} S_j}{d_B} \tag{3}$$

Define that the business volume handled by nodes per unit time is C_u, the weight of business nodes can be calculated as:

$$W_B = \frac{C_u}{C_B} \tag{4}$$

Thus, the business network can be represented by the matrix $A_B = [a_{ij}]_{\mathrm{n}\times\mathrm{n}}$, where the diagonal element a_{ii} is the weight of the business nodes, and the non-diagonal element is the connection relationship between the nodes. If there is an information interaction between nodes, $a_{ij} = 1$, otherwise $a_{ij} = 0$.

2.2 Physical Network

Physical network G_P is an undirected weighted network, expressed as $G_P = (V_P, E_P, W_P)$, where V_P represents a set of physical nodes (aircraft); E_P represents the set of edges, indicating the communication links between aircraft; W_P represents the set of physical node weights, which are determined by the aggregation degree [9]. The calculation process of physical node weight is as follows:

Calculate the aggregation degree α of G_P:

$$\alpha = \frac{n - 1}{\sum_{u \neq v \in V_P} d_{u,v}} \tag{5}$$

where n is the number of all nodes in the network, $n \geq 2$, $d_{u,v}$ represents the shortest distance between node N_u and N_u.

Thus, the node weight w_u can be calculated as:

$$w_u = 1 - \frac{\alpha(G_P)}{\alpha(G_P \times N_u)} \tag{6}$$

where $G_P \times N_u$ represents the graph after the N_u is shrunk. The shrinking N_u refers to the fusion of all k_u nodes connected with the node N_u, namely a new node replaces the $k_u + 1$ nodes. The edges originally associated with them are now associated with the new node.

Thus, the physical network can be represented by the matrix $B_P = [B_{ij}]_{n \times n}$, where the diagonal element b_{ii} is the weight of the physical node, and the non-diagonal element is the communication link between the nodes. If there is a communication link between nodes, $b_{ij} = 1$, otherwise $b_{ij} = 0$.

2.3 Business-Physical Interdependent Networks

According to the above analysis, the business nodes are coupled by the physical nodes. If the physical node N_P has multi-functions, there are corresponding multi-business nodes. Meanwhile, there is a one-to-multi dependency edge between the physical network and the business network. A physical node may be the basis of multiple business nodes, and a business node must rely on a physical node to function normally. $E_C = [e_{ij}]_{P \times B}$ represents the set of dependent edges between two-layer networks. If there is a dependent edge between physical node N_P and business node N_B, $e_{ij} = 1$, otherwise $e_{ij} = 0$.

In summary, a business-physical dependent network model for AANET can be built, represented by multiple groups BP = Θ (G_B, G_P, E_C).

3 Analysis Model Based on Failure Propagation Model

In this Section, a failure propagation model is selected to analyze node failures.

3.1 Traffic Reallocation Mechanism

When node failure occurs, the traffic on the failed node needs to be reallocated to adjacent nodes. Assume that the reallocation of the process is not uniformly distributed, but based on the weights between nodes. Define the increase of the traffic on the neighbor node N_j is ΔL_j:

$$\Delta L_j = \frac{w_i L}{\sum\limits_{S \in (N_n \in i)} w_S} \tag{7}$$

where, w_i is the weight of N_i, and N_i is the failed node. L represents the traffic that needs to be redistributed. w_s represents the weight of the neighbor nodes. Node weights are concerned with traffic reallocation to better analyze the failure propagation process. The bigger the node weight, the easier it is to propagate traffic. In the process of traffic reallocation, the traffic should be given priority to nodes with high weight, which can effectively reduce the scope and possibility of further node failures.

3.2 Failure Propagation Model

The failure propagation model [10] divides nodes in the network into two types: W (Working) and F (Failed). Defined that $W\ (t)$ is the number of working nodes at t time and $F\ (t)$ is the number of failed nodes at t time. When the working node fails due to its overload, it will be transformed into a failed node. The failed nodes can also be converted into working nodes after being repaired by corresponding means.

In the failure propagation model, each failed node is converted to a working node by conversion rate γ. Each working node is converted to a failed node by failed rate β, which can be expressed as

$$\begin{cases} W(t_1) + F(t_1) \xrightarrow{\beta} F(t_2) + F(t_2) \\ F(t_1) \xrightarrow{\gamma} W(t_2) \end{cases} \tag{8}$$

This model is characterized by the fact that the rates are influenced by both $W\ (t)$ and $F\ (t)$. Therefore, the proportion of working nodes and failure nodes in the network changes with time can be described by the following differential equation:

$$\begin{cases} \frac{dW}{dt} = -\beta WF + \gamma F \\ \frac{dF}{dt} = \beta WF - \gamma F \\ W(0) = N - F_0 \\ F(0) = 0 \end{cases} \tag{9}$$

where N represents the number of total nodes, βWF represents the number of increased nodes during the propagation from working nodes to failed nodes, γF represents the number of nodes increased during the propagation from failed nodes to working nodes, F_0 represents the number of failed nodes when the network started.

Finally, the ratio f is used in this paper to represent the node failure effect degree. The higher the value is, the worse the network security status is. Therefore, the operator of the effect value is:

$$f = \frac{F(t)}{N} \tag{10}$$

In this paper, the degree of node failure effect can be determined by the value of f. It is shown in Table 1.

Table 1. Network node failure effect degree.

f	[0, 0.2]	(0.2, 0.4]	(0.4, 0.6]	(0.6, 0.8]	(0.8, 1]
Degree	Very Minor	Minor	Moderate	Major	Very Major

4 Traffic Reallocation Strategy Based on Link Survivability

In this Section, we proposed a traffic reallocation strategy based on link survivability to improve the network invulnerability.

4.1 Link Survivability Calculation Module

Link survivability is proposed to measure the stability of a link between two aircrafts in a physical network. Link survivability is determined by the distance between nodes and the node failure rate. Assuming that all nodes in the network have available positioning information, the distance between the two nodes is estimated through mathematical modeling, and the corresponding calculation process is as follows:

Define that the longitude and latitude coordinates of N_A and N_B are (A_j, A_w) and (B_j, B_w), and the earth radius R is taken as 6371 km. Then the distance between the two nodes is:

$$d_{A,B} = R \times \arccos[\cos A_w \times \cos B_w \times \cos(A_j - B_j) + \sin A_w \times \sin B_w] \tag{11}$$

Using the inverse distance weighted interpolation method, the link weight $w_{A,B}$ between node N_A and N_B is:

$$w_{a,b} = \frac{1}{d_{A,B}^{\mu}} \tag{12}$$

where $\mu > 0$.

Thus, link survivability can be expressed as

$$\sigma = w_{A,B} \times \beta \tag{13}$$

where β represents the probability that a working node is converted into a failure node.

4.2 Traffic Reallocation Strategy Based on Link Survivability

When a node fails in the network, the traffic on the failed node needs to be reallocated to other neighboring work nodes. In this paper, the workflow design of the optimal traffic reallocation algorithm based on link survivability is presented as follows.

Step 1. The available neighbor nodes are stored in set N, the link information between failed nodes and neighbor working nodes is stored in set L, and the distance $d_{A,B}$ between nodes is calculated by using the link information stored in set L.
Step 2. The weight $w_{A,B}$ of each available link is calculated by inverse distance weighted interpolation.
Step 3. Calculate link survivability σ based on Eq. (11–13) and the average link survivability $\bar{\sigma}$
Step 4. Select available links according to link survivability σ.
Step 5. Calculate the weight w_i of available nodes and distribute the traffic to each available node according to the weight w_i.

5 Experiment and Analysis

To verify the validity of this model, it is applied to the AANET of a domestic airport. Taking the ADS-B data of March 5, 2019, as an example, the application process of the node failure model is illustrated below. From this AANET, the number of business network nodes and links are $V_B = 25$, $E_B = 24$, and the number of physical network nodes and links are $V_P = 50$, $E_P = 96$. According to the mapping relationship between two-layer nodes, a business-physical interdependent networks model can be constructed. The network initialization parameters are set as shown in Table 2.

Table 2. Network initialization parameters

Parameter	Initial value	Parameter	Initial value	Parameter	Initial value
γ_1	0.4	γ_2	0.4	μ	0.5
β_1	0.6	β_2	0.6		

5.1 Calculate Node Weight

Calculate the Business Node Weight. According to the calculation method of network traffic described in Sect. 2.1, the total network traffic at this time can be calculated as $C_B = 82\,973.85829$. Based on Eq. (4), the weight of business node is (see in Table 3):

Table 3. The weight of business node

No.	Weight	No.	Weight	No.	Weight
1	0.046130	11	0.004301	21	0.020930
2	0.049077	12	0.001501	22	0.057807
3	0.039373	13	0.010067	23	0.019462
4	0.031319	14	0.068827	24	0.059738
5	0.090923	15	0.101915	25	0.043774
6	0.091858	16	0.004329		
7	0.012851	17	0.038345		
8	0.011890	18	0.039458		
9	0.032172	19	0.032919		
10	0.005130	20	0.085900		

Calculate the Physical Node Weight. According to the method described in Sect. 2.2, the importance of physical network nodes is calculated as the weight of physical nodes, and the results are shown in Table 4.

Table 4. The weight of the physical node

No.	Weight	No.	Weight	No.	Weight	No.	Weight	No.	Weight
1	0.953455	11	0.906528	21	0.879105	31	0.893799	41	0.926799
2	0.858166	12	0.879962	22	0.884467	32	0.838961	42	0.880508
3	0.861346	13	0.871528	23	0.947392	33	0.880623	43	0.825233
4	0.872374	14	0.883541	24	0.952314	34	0.885750	44	0.900037
5	0.855380	15	0.845832	25	0.862411	35	0.853717	45	0.899340
6	0.840138	16	0.830429	26	0.858166	36	0.936378	46	0.915638
7	0.898922	17	0.909773	27	0.856616	37	0.856060	47	0.874517
8	0.864464	18	0.818002	28	0.840904	38	0.843213	48	0.817346
9	0.843866	19	0.929349	29	0.86260	39	0.875039	49	0.878512
10	0.873670	20	0.832370	30	0.889279	40	0.832714	50	0.867661

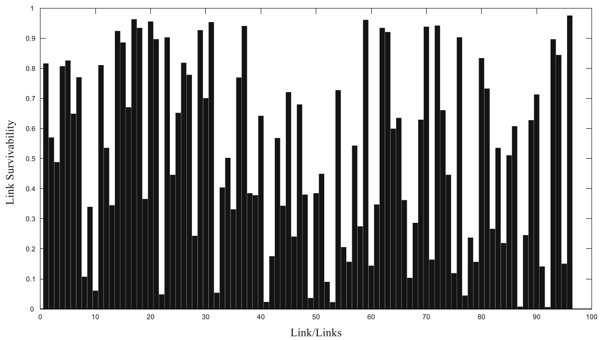

Fig. 1. Value of link survivability

5.2 Calculate the Link Survivability

According to Sect. 5, the physical network has 96 links. Then, based on the link survivability calculation module, the survivability of each link is shown in Fig. 1.

5.3 Analysis of Node Failures for Different Attack Modes

Random Attacks. Under the random attack, the ML (Motter-Lai) model [6], the WR (Weight based Redistribution) [7] model, the FP (Failure Propagation) model [10], and the model proposed in this paper are respectively used to analyze the node failure and impact on AANET. The results are shown in Fig. 2.

When the network is attacked randomly, no matter which kind of interdependent networks node failure model is used, the network will be affected at the beginning, and the affected degree will increase, and then become stable. Compared with other models,

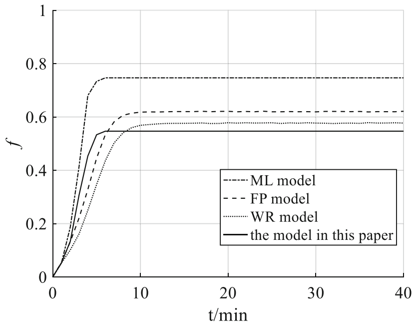

Fig. 2. The degree of network node failures of random attacks

the final state of our model is "Moderate". Obviously, the loss of the network caused by the model proposed in this paper is significantly lower than that of other models, and the stability of the network is also significantly improved.

Deliberate Attacks. The four models are attacked respectively by deliberate attacks. The results are shown in Fig. 3.

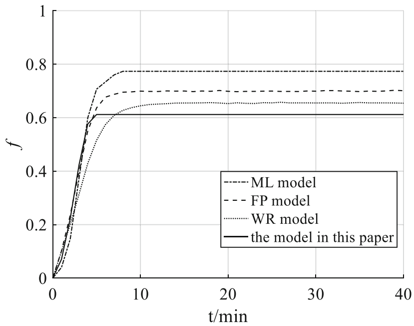

Fig. 3. The degree of network node failures of deliberate attacks

The final state of the four models is "Major". But the loss of the network caused by the model proposed in this paper is significantly lower than other models. It also can be seen from the comparison that under the condition of deliberate attack intensity, the influence of deliberate attacks on the network is obviously greater than that of random attacks. This is due to the high traffic of the key nodes themselves, and once the failure occurs, other nodes will be difficult to carry the reallocated traffic, thus generating node effect and causing large-scale damage to the network easily and rapidly. The reasons why this happened are as follows.

a. The model proposed in this paper takes into account the actual factors of the network. The crash of the network is not only the interaction between the physical nodes but also the interaction between the two layers of nodes, which means the physical nodes are controlled by the business nodes. Therefore, this paper increases the consideration of the AANET business network, which makes the model more consistent with the actual situation.

b. AANET is a highly dynamic and self-organizing network, so this paper proposes a link survivability strategy based on the distance between physical nodes. Assign smaller weights to distant nodes and larger weights to near nodes. Combined with the failure rate of network nodes to obtain the link survivability. The traffic reallocation path is optimally selected to make the network better reduce network losses and improve the invulnerability of the network after being attacked.

6 Conclusion

In this paper, the analysis model of node failures and impact for AANET is proposed. The business node weight is calculated through the node volume and network volume, and the physical node weight is calculated according to the node aggregation degree. The failure propagation model is used to analyze the failure process of the network, and the value of the effect caused by the node failures on the network is obtained and the degree of the network affected is judged. Finally, this paper proposes a traffic reallocation strategy based on link survivability. The link is selected according to the overall consideration of link survivability and node failure rate. The traffic is reallocated by node weight. The experiment shows that compared with other model, the model proposed in this paper has better stability and invulnerability.

References

1. Kumar, V.: Aircraft ad-hoc network (AANET). Int. J. Adv. Res. Comput. Commun. Eng. **3**(5), 6679–6684 (2014)
2. Jose, C.G.: Control of communications-dependent cascading failures in power grids. In: 2019 IEEE Power & Energy Society General Meeting (PESGM), Atlanta, p. 1 (2019)
3. Sergey, V.B.: Catastrophic cascade of failures in interdependent networks. Nature 1025–1028 (2010)
4. Wang, Z.: Cascading risk assessment in power-communication interdependent networks. Physica A: Statal Mech. Appl. 540 (2019)
5. Zhang, L.: Study on the cascading failure model of double-layer coupling network, In: 2018 Chinese Control and Decision Conference (CCDC), Shenyang, pp. 4586–4590 (2018)
6. Chen, Z.: Cascading failure of interdependent networks with different coupling preference under targeted attack. Chaos Solitons Fractals 7–12 (2015)
7. Han, L.: Cascading failure model of weighted scale-free networks. J. Softw. **28**(10), 2769–2781 (2017)
8. Peng, H.: Cascading failures and security assessment of information physics system under intentional attack strategy. J. Zhengzhou Univ. **51**(03), 13–21 (2019)
9. Wu, J.: Evaluation method for node importance based on node contraction in complex networks. Syst. Eng.-Theory Practice **26**(11), 79–83 (2006)
10. Gong, W.: Research on the stability and control of computer virus network communication model. Wireless Internet Technol. 24–25 (2015)