Reliability Modeling and Analysis of SCI Topological Network

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***Abstract*—The problem of reliability modeling on the Scalable Coherent Interface (SCI) rings and topological network is studied. The reliability models of three SCI rings are developed and the factors which influence the reliability of SCI rings are studied. By calculating the shortest path matrix and the path quantity matrix of different types SCI network topology, the communication characteristics of SCI network are obtained. For the situations of the node-damage and edge-damage, the survivability of SCI topological network is studied.**

***Index Terms*—SCI, topology structure, shortest path, Monte-Carlo method**

I. INTRODUCTION

The Scalable Coherent Interface (SCI), which is widely used in high-performance distributed computer network and I/O system, has already become a standard interface technology of the structure of avionics system in the advanced 4th generation fighter [1].

The U.S. army's avionics research program Joint Advanced Strike Technology (JAST) uses the SCI network as the principal protocol in its integrated avionics system so as to replace the 7 types of data-bus and network communication technology [2]. The simplification by using SCI network improves the system performance and reliability and reduces the system cost as well.

Presently Chinese 4th generation fighter has neither been served formally nor established the final framework technology of its avionics system. Therefore, research on the advanced structural technology applied in the foreign equipment has a positive worthiness for the development in this domain.

References [3, 4, 5] defined the SCI network reliability as the probability when all parts of the SCI network were in normal status. References [6, 7] proposed the concept of task-based network reliability of distributed computing system, but did not take into account of the reliability of components. References [8, 9] studied the SCI distributed system using the concept of fault tolerance, but did not make a discussion on the factors which influence the reliability of SCI rings. References [10, 11] carried out the research on the viability of SCI network, but did not take the analysis of its time-delay characteristic into account.

Taking into account of the problems of current research, this paper introduces the conception of network reliability based on the source-destination message in SCI network, combined with message flow control mechanism of the Interface Control Documents (ICD). Reliability modeling of different types of SCI topological structure is established and analyzed. From the conclusions and methods of the articles mentioned above, this paper proposes the quantificational evaluation method of the communication accessibility of SCI network and gives comparison analysis of different types of SCI topology

II. RELIABILITY MODELING AND ANALYSIS OF SCI-RING NETWORK

A. Mechanism of SCI-Ring network

The SCI system interconnection structure consists of a series of Interface Units (IU), Switch Modules (SM) and Link Modules (LM)[12], as shown in Fig.1. According to different requirements of the task and the load, these three units can compose different forms of flexible interconnection structure topology and provide the bandwidth accordingly. For example, the SM of one-way ring interconnection has one input and one output, while one-way TORUS interconnection has 2 inputs and 2 outputs. Butterfly interconnection with 12 nodes consists of three types of SM[13].

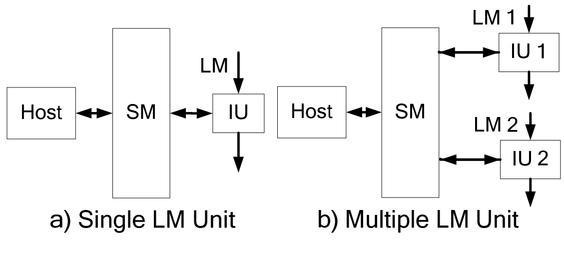

Figure 1. Basic units of the SCI rings

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B. Reliability model of SCI-Ring Network

The premise for the SCI interconnection with multiple nodes has three terms:

a) All nodes in the SCI interconnection consists of three pure components: IU, SM and LM. There is no coupling between nodes.

b) All of the three types of components exist in two states: normal or fault.

c) Partial failure will cause the host to lose the ability to send messages, while global failure in the host will result in a communication failure [14].

In the IDC file of avionics system, messages from a source node reach the destination node through a series of intermediate nodes. The property of message in the SCI system is defined by ICD file, which can be described in the Interconnection Matrix (IM)[15]. The rows of IM represent the source of SM, while the columns represent the destination. The value of IM matrix can only be 1 (connect directly) or 0 (no connection). The IM of n-node SCI system can be expressed as C in (1):

$$C = \{l_{ij}\} \qquad i = 1,2.....n;\ j = 1,2.....n$$
$$l_{ij} = \begin{cases} 0 & connection\ between\ i\ and\ j \\ 1 & no\ connection\ between\ i\ and\ j \end{cases} \tag{1}$$

The ICD provides the format of message exchange in SCI system, including information on the source, destination, renewal rage, length and max delay time. The life cycle of a message starts from the source node and ends at the destination node. For the SCI system composes of multiple nodes, the same message may have more than one path.

As mentioned above, each message may correspond to more than one path. The message delivery is affected not only by the three basic aspects (IU, SM and LM), but also the number and length of the message path, which is defined by ICD files.

The symbol M_{ij} represents a message from node i to node j, and then the message set Ms of the SCI system is composed by M_{ij} in (2).

$$M_s = \{M_{i,j} \,|\, i = 1....n,\ j = 1....n\} \tag{2}$$

The symbol $r_{i,j}$ represents a possible node in the transmission path M_{ij}, and then all of the $r_{i,j}$ form the path set M_{ij}. A single path $r_{i,j}$ is composed of the set of NU, SM and LM, which can be represented by $Nr_{i,j}$, $Sr_{i,j}$, and $Lr_{i,j}$.

The reliability of a single path $r_{i,j}$ in a message delivery M_{ij} is defined as follows in (3).

$$\begin{aligned} D_{i,j} &= P_r\left|r_{i,j}\right| = P_r\left|I_{ri,j} \cap S_{ri,j} \cap L_{ri,j}\right| \\ &= P_r\left|I_{ri,j}\right| * P_r\left|S_{ri,j}\right| * P_r\left|L_{ri,j}\right| \end{aligned} \tag{3}$$

The symbol $P_r\,|*|$ indicates the probability of normal operation of the corresponding parameter inside. Taking into account of the different paths of a message delivery M_{ij}, we can get the reliability of message delivery in (4).

$$\begin{aligned} R_{i,j} &= P_r\left|M_{i,j}\right| = 1 - \prod_{k_{i,j}} (1 - D_{i,j}) \\ &= 1 - \prod_{k_{i,j}} (1 - P_r\left|I_{ri,j}\right| * P_r\left|S_{ri,j}\right| * P_r\left|L_{ri,j}\right|) \end{aligned} \tag{4}$$

The symbol $K_{i,j}$ in (4) indicates the number of paths $r_{i,j}$ in the message transmission M_{ij}. When all paths $r_{i,j}$ of a message delivery M_{ij} fail, the message delivery M_{ij} gets lost completely.

The reliability of the SCI system R_s denotes the probability of normal operation that all messages are passed correctly. From the definition, the network reliability can be obtained from (5):

$$R_s = \prod_{i=1}^{n} (\prod_{j=1}^{n} R_{ij} * l_{ij}), \quad l_{ij} \in C \tag{5}$$

C. Application of Reliability Modeling on SCI-Ring Network

The current applications of SCI interconnection in avionics system often use three typical structures: Single Ring (SR), Independent Double Ring (IDR) and Cross Double Ring (CDR).

In order to simplify the equation, we can use the symbol F_s for denoting the failure rate of a single SM, while F_i denoting the failure rate of IU and F_i denoting the failure rate of LM.

Considering the SCI single ring model with n nodes, as shown in Fig.2, the reliability can be obtained from (6)

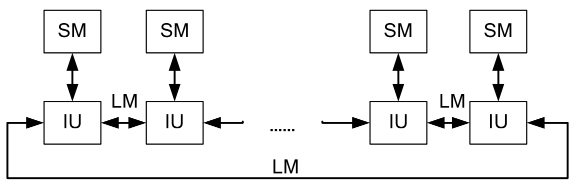

Figure 2. Structure of single ring

$$R_{SR} = (1 - F_I)^N (1 - F_S)^N (1 - F_L)^N (1 - F_H)(1 - \alpha F_S)^{N-1} \tag{6}$$

The symbol α in (6) indicates the global failure rate of SM in the structure of SCI rings while F_H indicating the failure rate of globe host. The symbol N indicates the number of independent structures in the SCI interconnection system.

The IDR and CDR of SCI rings are very similar in structure, as shown in Fig.3 and Fig.4. The difference between them is that the two loops of IDR are separate and independent, while CDR can always communicate.

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Obviously, the CDR of SCI rings has to be more flexible but also complex.

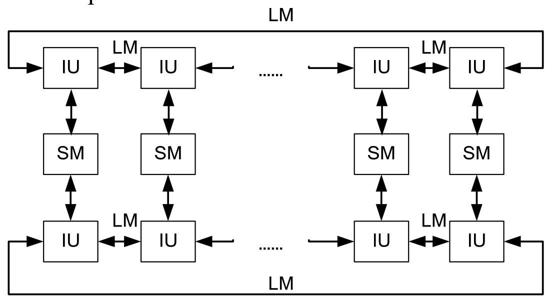

Figure 3. Structure of independent double ring

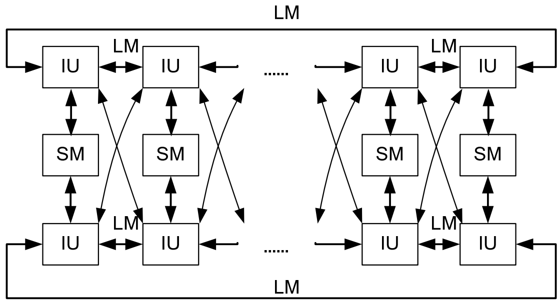

Figure 4. Structure of cross double ring

Considering the IDR and CDR of SCI rings with n nodes, as shown in Fig.3, the reliability can be obtained as follows according to (7) and (8).

$$R_{IDR} = (1-F_S)^N (1-F_H)(1-\alpha F_S)^{N-1}\{1-[1-(1-F_L)^N (1-F_I)^N]^2\} \quad (7)$$

$$R_{CDR} = (1-F_S)^N (1-F_H)(1-\alpha F_S)^{N-1}\{1-[1-(1-F_L)^2 (1-F_I)]^2\}^N \quad (8)$$

D. Reliability Analysis of SCI-Ring Network

The impact of failure rate of SM, IU and LM on the reliability of SCI rings will be studied under the initial assumptions in (9).

$$\begin{aligned} F_H &= 10^{-3}, \alpha = 0.1, N = 20 \\ F_S &= F_L = F_I = 10^{-4} \end{aligned} \quad (9)$$

The initial value is not necessarily consistent with the failure rate of actual component; however, it is valuable and necessary for the research of reliability. To accurately reflect the failure rate of the whole SCI rings, the failure rate of components will be examined in a large dynamic range from 10^{-5} to 10^{-1}. From Fig.5, the failure rate of SM has the same impact on the three different structures. This is because the role and position of SM in the three different structures are similar. With the increasing failure rate of SM, the reliability of the three structures decreases rapidly. The failure rate of IU and LM on the three different structures has different effects. The SR is the most sensitive with the failure rate of IU, while CDR is the most stable.

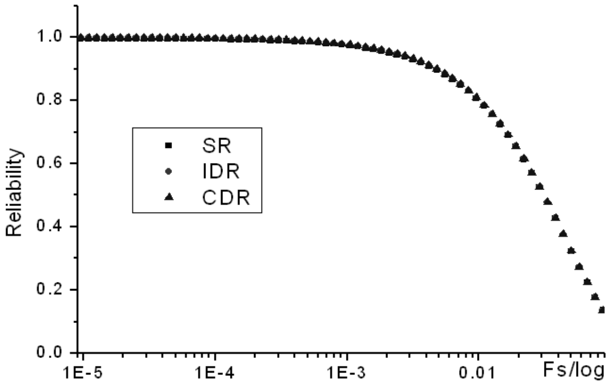

Figure 5. Influence of reliability of SM on SCI rings

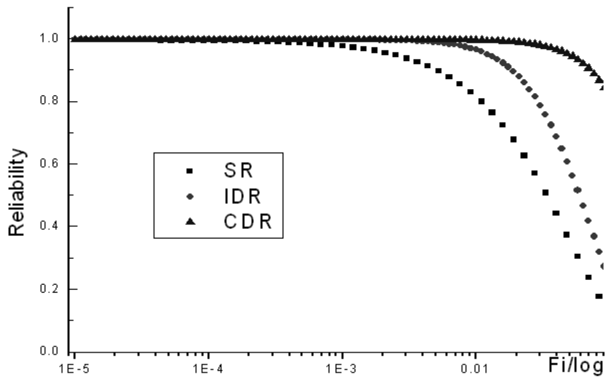

Figure 6. Influence of reliability of IU on SCI rings

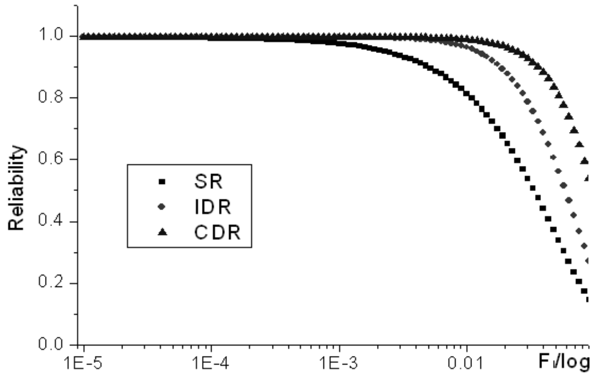

Figure 7. Influence of reliability of LM on SCI rings

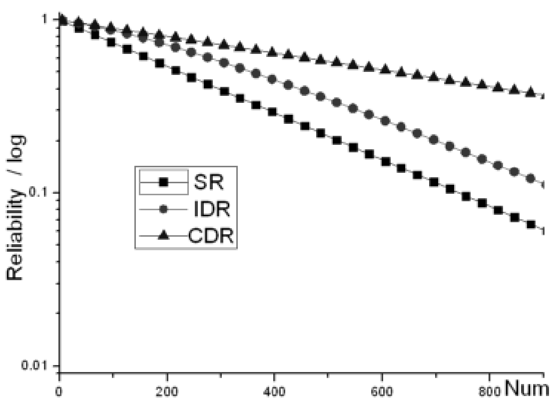

Figure 8. Influence of node quantity on system reliability

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As the scale of nodes increases, the system complexity of the SCI rings will increase and reliability will decrease. From Fig.8, we can see that the CDR is the least sensitive to the scale of nodes. This prompts us that redundant components can be suitably increased to improve reliability in the design of complex SCI avionics system.

From the reliability theory, the CDR of SCI rings provides the highest reliability and flexibility, but for engineering applications, the CDR may not be the best option because of its complexity and cost.

III. Connectivity Performance and Survivability of SCI Topological Network

A. *Topological structure of SCI network*

Generally, the nodes composing the SCI network have dual or more I/O interfaces so as to connect two communication rings. Four types of topological structure namely as Normal Grid (NG), Butterfly-Cross Grid (BCG), Normal Derivation-1 Grid (NDG_1) and Normal Derivation-2 Grid (NDG_2) are regarded as the prototype of SCI interconnection network[16]. The quantity of SCI network in JSF avionics system is about 20 based on the JAST program, so this paper adopts the 16-node matrix as the dimension of research object.

The NG topological structure is the most common type in SCI interconnection network. As in Fig. 9, the four nodes in each row and column compose a single closed ring, while every node is connected with two independent rings.

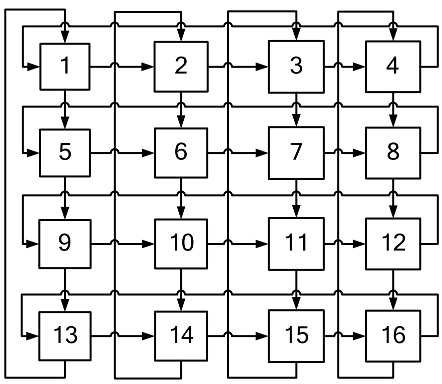

Figure 9. NG topological structure

The BCG topological structure is also widely adopted in the construction of SCI interconnection network. As in Fig. 10, the four nodes in every row compose a single ring, while the four nodes in the oblique direction compose another SCI ring. Similar to the node in NG type, each node in BCG is connected with two independent rings.

The 16 nodes of NDG_1 topological structure compose 8 interconnection rings, which are listed as follows: (1,2,6,5), (3,4,8,7), (9,10,14,13), (11,12,16,15), (6,7,11,10), (2,3,15,14), (5,8,12,9) and (1,4,16,13), as in Fig. 11.

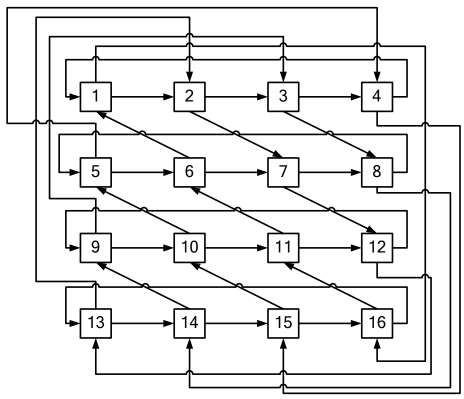

Figure 10. BCG topological structure

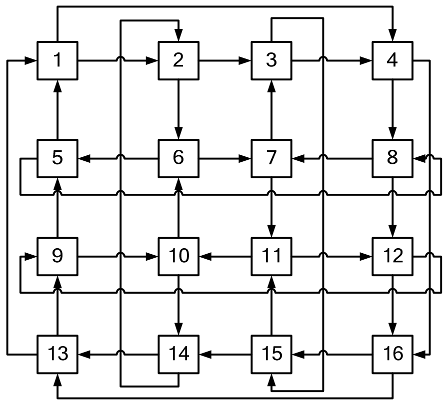

Figure 11. NDG_1 topological structure

The 8 independent rings of NDG_2 topological structure are listed as follows: (1,2,6,5), (2,3,7,6), (3,4,8,7), (9,10,14,13), (10,11,15,14), (11,12,16,15), (1,5,9,13) and (16,12,8,4), as in Fig. 12.

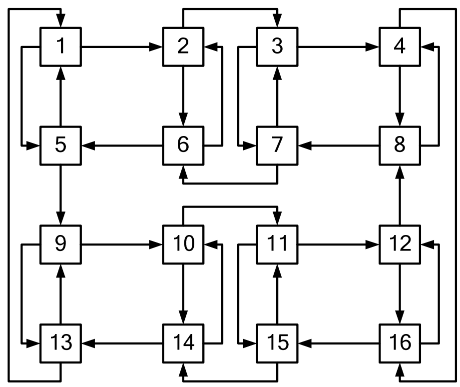

Figure 12. NDG_2 topological structure

The four types of topological structure mentioned above have some similar properties. The 16 nodes of them compose 8 independent interconnection one-way rings and each node is connected with two independent rings. The data-flow direction will affect the performance of SCI interconnection network to a certain extent. In order to give an integrated performance analysis of the 4 types of SCI topological structure, an assumption of the same data-flow direction in the rings is set as a precondition.

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B. Connectivity algorithm and analysis

According to the definition of AM of SCI network, the column num of non-zero elements in row i denotes the nodes' index with which node i connects directly, while the row num of non-zero elements in column j denotes the nodes' index that node j connects directly. The Interconnection Matrix (IM) can be deduced from the AM of SCI network as in (10).

$$P=\sum_{t=1}^{n} C^{t} \tag{10}$$

The column num of zero-element in row i denotes the nodes' index where there is no route from node i to these nodes. Therefore, the connectivity performance of the whole SCI network can be concluded from the inspection that if there is zero-value element in IM.

According to the routing theorem of graph theory[17], if matrix C is the AM of an oriented network, then the matrix $T=C^m$ can be concluded and its element $t(i,j)\in T$ denotes the route amount from node i to node j when the route length is limited as m.

The shortest routing matrix S and the routing amount matrix T can be obtained based on the application of AM. The algorithm is described in Fig. 13.

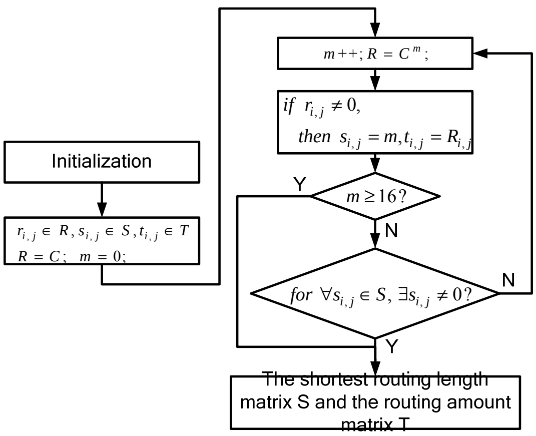

Figure 13. Connectivity performance algorithm

According to the routing theorem, if the distance between two adjacent connected nodes is defined as one unit[18], the elements $s(i,j)\in S$ denote the node amount of the shortest routing from node i to node j. The connectivity index of SCI topological network can be described using its shortest routing matrix S and routing amount matrix T [19]. The shortest routing matrix S affects its time-delay property and pay-load capacity, while the routing amount matrix T affects its anti-damage capacity. The shortest routing matrix S and routing amount matrix T of the four types of SCI topological structure can be obtained by using the connectivity algorithm proposed above. In order to compare the four types of SCI topological network, we calculate the algebra average of matrix S and T. The results are shown in Table 1.

TABLE. 1
ANALYSIS RESULT OF CONNECTIVITY PERFORMANCE

Topological type	Average length of the shortest routing	Average amount of the shortest routing
NG	3.7500	5.0000
BCG	3.3398	2.0430
NDG_1	3.2500	2.0000
NDG_2	3.2500	1.2500

The average length of the shortest routing is one of the most important factors for the time-delay performance of the whole SCI network[20]. The lower this parameter gets, the shorter the routing path from source node to destination node and the communication time-delay gets. Meanwhile, this parameter also determines the nodes amount in the data-flow communication, so it will also affect the reliability of SCI communication. The average amount of the shortest routing determines the optional amount of shortest routing, therefore, the higher this parameter gets, the higher the communication safety and anti-damage capacity gets.

In the four types of SCI topological networks discussed above, the NDG_2 has the shortest routing, which is due to the connections between two distant nodes which reduce the amount of repeater nodes. The NG has the most average amount of routings. Most routes in NG type of SCI topological networks have to go through at least two rings, which provide a fairly complex combination of routing segments.

C. Survivability evaluation algorithm and analysis

The survivability of SCI topological network is the probability that the permanent components maintain effective communication when some nodes or circuitries encounter failure. The survivability analysis is based on the interconnection algorithm of SCI topological network. Its basic method is to process the connectivity analysis for the permanent components on the assumption that some nodes or circuitries have been damaged.

There are two types of damages. Survivability on node-failure means the probability that the permanent nodes still maintain interconnection when n nodes are damaged. Survivability on circuitry-failure means the probability that all nodes maintain interconnection when n circuitries are damaged.

Both node and circuit failure will affect AM of SCI topological network. For the condition of node failure, all elements of AM connected with those damaged nodes should be cleared to ZERO. While for circuitry-failure condition, the elements of AM corresponding with the damaged circuitries should be cleared to ZERO.

The survivability evaluation algorithm randomly selects n nodes or circuitries as the damaged parts, updates its AM every time and finally use the interconnection algorithm proposed above to make a check if the whole updated AM is interconnected. Using Monte-Carlo method, for each condition where n nodes or circuitries are damaged, L_t times of random sample selection are processed. If the result is that there are no zero elements in the IM based on the updated AM of SCI topological network emerges for Lz times, the

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survivability S_n for n nodes or circuitries failure can be obtained by (11).

$$S_n = {(1 - Lz)}\Big/{L_t} \times 100\% \qquad (11)$$

For the four types of SCI topological network mentioned above, the survivability evaluation results are given in Table 2 and Table 3, at the sample amount of 1000 for each condition.

TABLE. 1
SURVIVABILITY RESULTS IN NODE-DAMAGE CONDITIONS

Topological type	Amount of damaged nodes		
	1	2	3
NG	100%	82.6%	62.8%
BCG	100%	79.4%	58.4%
NDG_1	100%	73.3%	42.8%
NDG_2	100%	55.1%	22.1%

TABLE. 2
SURVIVABILITY RESULTS IN CIRCUITRY-DAMAGE CONDITIONS

Topological type	Amount of damaged circuitries		
	1	2	3
NG	100%	93.5%	81.5%
BCG	100%	90.2%	79.8%
NDG_1	100%	92,1%	80.2%
NDG_2	100%	82.1%	50.8%

These four types of SCI topological network all have the primary anti-damage ability. In the case where one node or circuitry encounters failure, the probability that permanent parts of SCI topological network still maintain connectivity is 100%. The anti-damage capacity is due to the fact that every node connects SCI network through two independent communication rings. The primary anti-damage survivability is also the reason that SCI topological network is regarded as an important development of topological structure of the advanced avionics.

The NG, BCG and NCG_1 types have similar survivability capacity. Compared with the other three types, the NG type's survivability capacity is preponderant. If two nodes encounter failure, the NG type's probability of maintaining connectivity is more than 80%. If two circuitries are damaged, the NG type's probability of maintaining connectivity is above 90%.

Compared with the condition of node failure, these four types of SCI topological network have a higher survivability to tolerate circuitry loss. At the loss of three circuitries, the NG, BCG and NCG_1 types still maintain connectivity rate at 80% level; however, if three nodes encounter failure, the connectivity rate is only about 40%~60%. The feature is due to the reason that every node failure will also result in the failure of two circuitries.

III. Conclusions

This paper has conducted a comprehensive analysis on the path characteristics of SCI topological network and has come to the following conclusions.

With the increasing failure rate of components, the reliability of the three structures as SR, IDR and CDR decrease rapidly. The CDR of SCI rings provides the highest ability to tolerant component fault; however, it may be not the best option in engineering application because of its complexity and cost.

For a specific type of SCI topology, the performances of average routing length and average routing amount are often contradictory, so it is difficult to achieve the best performances at the two aspects simultaneously. In the actual design, the type of SCI topological network should be determined by the system requirements and the specific device properties.

All these four types of SCI topological network have the primary anti-damage ability. Compared with the condition of node failure, SCI topological network has a higher survivability to tolerate circuitry loss.

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