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**Research Article**

# Dynamic Evolution in Social Cooperation Networks with Node Failure

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**Abstract:** Social cooperation networks are a kind of social networks in which individuals are linked through cooperation. Interference of economic crises, natural disasters and other emergencies may cause the node fails in social cooperation networks. To further study the influences of node failure on the total fitness degree and the cooperative ratio in social cooperation networks, the update rules of individual strategy and networks self-repair are constructed on the basis of the social cooperation networks and evolutionary game theory. For different types of social cooperation networks, the dynamic evolution in the cooperation networks with node failure is respectively analyzed by the agent-based simulation experiments. Simulation results show that the node failure not only reduces the total fitness degree of various social cooperation networks, but also reduces the cooperative ratio in two-group and multi-group cooperation networks. However, in the single-group cooperation networks, the cooperative ratio is improved by node failure. In addition, by introducing the self-repair rules, the emergence of a few of new cooperative nodes can break the stable state and promote the total fitness degree and the cooperative ratio of cooperation networks.

**Keywords:** Evolution, node failure, social cooperation networks, simulation experiment

## INTRODUCTION

The emergence of "small world" networks (Watts and Strogatz, 1998) and scale free network model (Barabási and Albert, 1999) has brought the study of complex networks to a new crescendo. It is generally assumed that complex networks can be divided into social networks, information networks, technology networks and biological networks (Zhang, 2006). Social networks where individuals are linked with each other by cooperation are called social cooperation networks (Ramasco *et al*., 2004). The individual in social cooperation networks are generally a single person and may alse be a group of people, a corporation, a company and so on. The most famous social cooperation networks include actor cooperation network (Adamic and Huberman, 2000; Newman, 2001a), scientist cooperation network (Newman *et al*., 2001b) and so on.

As a kind of complex system, social cooperation network is constantly evolving. The network structure can be regard as the evolvement of members' cooperative relationship. During prolonged evolvement, social group structure has stabilized to a certain extent among the members of network, but in each cooperation project, the individuals can still choose their strategies between cooperation and un-cooperation. After Axelord brought repeated PD game model to the research of cooperation, the evolutionary game theory has been widely applied as a significant tool to study social cooperation (Wang *et al*., 2008; Chen *et al*., 2009). The basic method is that individuals update strategies based on fitness degree which depends on frequency of contact with their neighbors, in other words, individuals imitate and study from neighbors by repeated game and finally the system reaches stabilization and equilibrium. In social cooperation networks, PD exists in many aspects such as information sharing (Zhao and Xiao, 2007) and products pricing (Gao, 2004) so the repeated PD game model has become the standard model for studying the social cooperation network. Nowadays, based on PD game model, Nowak (2006), Hauert and Doebeli (2004), Szabó *et al*. (2005) and some other scholars have studied the emergence and dynamic evolution of cooperation on different network topology structures.

In social cooperation networks, individuals may secede from the cooperation networks for the outside interference. When the node failure causes the large node vacancy in social cooperation networks, the cooperation interrupt. The interference may come from economic crises, policy changes and other social factors

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and may also come from terrorist attacks, natural disasters and other emergencies. The failure of node influences the structure of the social cooperation networks to a certain extent. Nowadays, the research of the influence of node failure on social cooperation networks focuses on microcosmic strategy of emergency management (Yang *et al*., 2009; Yan *et al*., 2010). Some other scholars study strategic evolution in social cooperation network considering the systematic science (Nair *et al*., 2009). In addition, various mechanisms affecting cooperation are also explored from a wide perspective of complex network (Wu and Wang, 2007; Hou *et al*., 2008). Although previous literatures have researched on cooperation of social networks from different sides, node failure which is an influential factor with wide realistic significance is seldom discussed. With the development of economic globalization, the social cooperation networks become more and more popular. So it is significant to treat with node failure caused by different emergencies.

In this study, the update rule of individual strategy is constructed on the basis of the social cooperation networks model and the dynamic evolution model in social cooperation networks is established with node failures. By the agent-based simulation experiments, the influence of node failures on the total fitness degree and cooperative ratio is analyzed in various social cooperation networks. In addition, the self-repair process of social cooperation network with note failures is simulated and analyzed.

## MODEL OF DYNAMIC EVOLUTION IN SOCIAL COOPERATION NETWORK WITH NODE FAILURES

**Social cooperation networks:** Social cooperation network is a special social network in which individuals are individuals are linked through cooperation. For example, in scientific cooperation network, each researcher is regarded as a vertex. That two vertexes are linked by a line denotes two researchers have published an article together. In general, the entire structure of social cooperation network has a characteristic of complex network.

Individuals in social cooperation network may come from the same characteristic group and may come from the different characteristic groups. For instance, scientists in scientific cooperation network may come from the same field and may come from the different; enterprises in virtual enterprise network may belong to the same value chain or the different. In this study, the social cooperation network is divided into three categories, namely, single-group cooperation network which has only one kind of the same characteristic node, two-group cooperation network with two different kinds of characteristic note and multi-group cooperation network, as shown in Fig. 1. Individuals in network form a certain cooperative by a long-term interaction. Every individual has different number of partners and different abilities of gaining information. Taking two-group cooperation network as an example, network model is built in the following way:

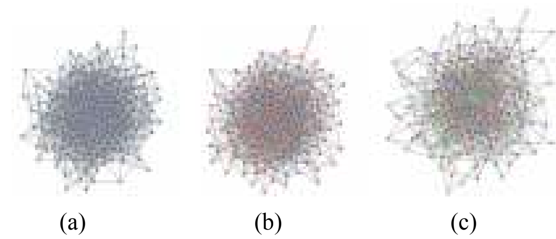

Fig. 1: Social cooperation network model; (a) single-group, (b) two-group, (c) multi-group

Table 1: Game matrix of A and B

| A/B | C | D |
|---|---|---|
| C | *b-c*, *b-c* | *-c*, *b* |
| *D* | *b*, *-c* | *0*, *0* |

Table 2: Transformed game matrix of A and B

| A/B | C | D |
|---|---|---|
| C | 1, 1 | *-r*, *1+r* |
| *D* | *1+r*, *-r* | *0*, *0* |

- Form an initial social cooperation network with $n=n_1+n_2$ nodes, where $n_1$ and $n_2$ denote the nodes' number of group 1 and group 2 respectively.
- Suppose the individuals in social cooperation network have formed a relatively fixed cooperative relationship. $p_{ij}$ ($i$ = 1, 2; $j$ = 1…$n_i$) denote the individuals' capacity of selecting partners and they reflect individuals' reputation, strength and other indexes. $q_{ij}$ ($i$ = 1, 2; $j$ = 1…$n_i$) denote the individuals' capacity of studying from neighbors, namely, the ability of gaining information.
- Individuals are irregularly matched by $p_{ij}$ and then one two-group social cooperation network is formed.

The constitutions of single-group and multi-group cooperation networks have the similar process.

**PD Game model:** PD game is a classical example in studying cooperation. In a PD game, individuals can get benefits from Cooperation strategy (C). But because of the temptation of Defection strategy (D), both sides of the game will finally choose defection. Its beneficial matrix can be written as follows (Table 1):

where, $b$ denotes cooperative benefit, $c$ is cooperative cost. In order to discuss conveniently, define $b$-$c$ = 1. And $r = c/(b-c)$ denotes cost-benefit rate. So the above model can be transformed into a single variable form (Table 2).

Though Nash equilibrium strategy of the one-off PD game is (D, D), according to Axelrod's theory (Axelrod and Hamilton, 1981), cooperation can come forth in the PD game with unlimited or the game with unknown deadline.

**Update of individual strategy:** Social cooperation network is a complex system, its structure constituted by individuals' intercourse is not static. By game and study with partners, individual updates his game strategy continually and then adjusts his relationship with others. This kind of strategy update among individuals promotes the emergence of the holistic cooperative characteristic in network.

In single-group cooperation network, because the nodes have the same characteristic, so we suppose that individual's partners (game neighbors) is just nodes from which individual learns strategic (learning neighbors). In two-group cooperation network and multi-group cooperation network, suppose that each node only games with the nodes of other group and only learn strategy from the nodes in the same group. In one game, the sum of the incomes of each node is assumed as:

$$U_i = \sum_{j \in \Omega_i} K_{ij}$$

we call the $U_i$ as fitness function. Where $\Omega_i$ denotes the game neighbors of node $i$ and $K_{ij}$ is the incomes of $i$ game with node $j$. Every node chooses one learning neighbor to compare their fitness degrees. Because someone is always looking for higher benefit, so the strategy of node with high benefit is easily imitated by others. Therefore, suppose nodes update their strategies by the following way (Wu and Wang, 2007):

$$P_{ij} = \frac{1}{1+\exp[(U_i - U_j)/k]} \quad (1)$$

where $P_{ij}$ denotes the probability of node $i$ taking the strategy of $j$, $U_i$ and $U_j$ denotes the incomes of the $i$ and $j$ respectively. And $k$ is noise coefficient, which denotes the strategy of node with low benefit may be imitated with little possibility because the bounded rationality. Define the network's cooperative ratio as:

$$\rho_c = {n_c}/{n} \quad (2)$$

where, $n_c$ denotes the number of cooperative nodes. Let $U = \sum_{i=1}^{n} U_i$ be the total fitness degree, namely, the sum of all nodes' fitness degree. We mark the best state of social cooperative network as $f = f(\rho_c, U)$ which is decided by both the cooperative ratio and total fitness degree.

**Self-repair of network with node failure:** Let $L_n = [a_n, a_{n-1}, \dots a_1]$ denotes the set of the total fitness degree obtained within the latest $n$ evolvements and $a_i$ be the total fitness degree obtained in the latest $i$ evolvements. When network evolves to stabilization, the mean value of $L_n$ denotes the steady fitness degree, marked as $Q$. Let system's steady criterion is

$$\text{Max}L_n - \text{Min}L_n < e \quad (3)$$

where, $\text{Max}L_n$ and $\text{Min}L_n$ denote the maximum and minimum value of $a_i$ in $L_n$ respectively and $e$ is restrict constant.

Before node failure, nodes game and update strategy in the light of Table 2 and rule (1). Suppose the steady fitness degree is $Q_1$ before node failure. After node failure, nodes disappear randomly according to the interference degree $m$.

$$m = (m_1+m_2\dots+m_n)/n \quad (4)$$

where, $m_1$, $m_2$... $m_n$ denote the numbers of disappearance nodes of different kinds of group in multi-group cooperation network and $n$ is the total number of network's nodes.

The cooperative network's primary structure is destroyed by node failure and then the surviving nodes find the new game neighbors and learning neighbors. When system retunes to stabilization, we calculate the steady fitness degree once again and note it as $Q_2$. Comparing $Q_2$ with $Q_1$, if $Q_2<Q$, we let the system spring out a new node and then initialize its $p_{ij}$ and $q_{ij}$. In fact, there are many examples in real life, such as a new movie star, a new scholar or a new enterprise and so on. Generally speaking, the new node tends to choose cooperative strategy in first time, so as to receive its honor. So we suppose the new nodes' initial strategy is cooperation and the new node chooses game neighbors and learning neighbors according to their $p_{ij}$ and $q_{ij}$. When the new node chooses game neighbors, their reputation is a significant factor, so we let the new node chooses randomly several old nodes as game neighbors which take cooperative strategy within the near 3 games.

When system retunes to stabilization again, calculate $Q_2$ and compare with $Q_1$, if $Q_2$ still small then $Q_1$, a new node comes forth. This process is repeated until the system attains the original steady fitness degree.

## SIMULATION EXPERIMENT AND ANALYSIS

In the following simulation experiments, evolutions of cooperation are analyzed in single-group, two-group and multi-group network with node failure respectively. We take 1000 initial network nodes and assume that the number of individuals in every group is equal in all networks. Let $0 \le p_i \le 12$, $0 \le q_i \le 12$, $k = 0.1$, $r = 0.1$, $e = 3000$ and take $n = 100$ to record the results of

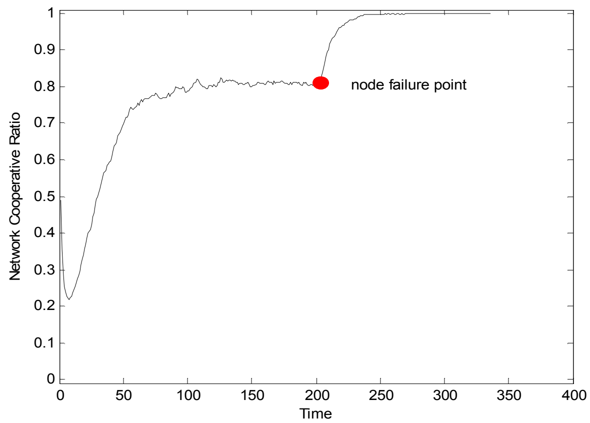


Fig. 2: Influence of node failure on the network's steady cooperative ratio in single-group cooperation network

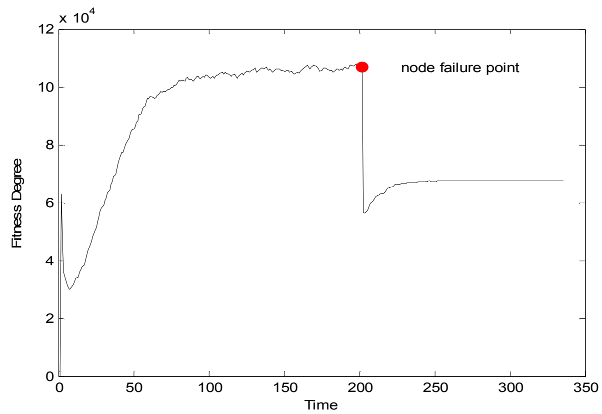


Fig. 3: Influence of node failure on the fitness degree in the Single-group cooperation network

$L_n$. The node's game benefits are calculated by Table 2. In this study, three-group cooperation network will represent multi-group cooperation network. In initial states, each individual chooses his game neighbors and learning neighbors randomly by neighbors' $p_{ij}$ and $q_{ij}$. When the system reaches stable, $m$ nodes disappear randomly to simulate the emergence of note failure. Then the evolutions of cooperation are observed and analyzed in different kinds of networks. In the following paragraph, we will describe the influence of node failure on cooperative ratio and total fitness degree first and then analyze how network cooperative ratio changes with different interference degree.

At last, we will take the two-group cooperation network as the general example to do a further simulation experiment on the evolution of cooperation with network's self-repair rules. In this part, we take 2000 initial network nodes, $0 \le p_i \le 12$, $0 \le q_i \le 8$, $e = 300$ and keep other parameters unchanged. The network's self-repair rule with node failure operates according to the previous paragraph. The dynamic evolution of cooperation with node failure is discussed with the effect of network's self-repair rule. At the same time, the relationship between steady network fitness degree and interference degree with node failure and the relationship network between interference degree and the number of new nodes required by network self-repair are given.

**Influence of node failure on network cooperative ratio and total fitness degree:** In single-group network, the network cooperative ratio trends to be steady gradually when the network's cooperative total fitness degree becomes stable. Here, node failure promotes the network cooperative ratio greatly (Fig. 2), but decreases the total network fitness degree rapidly (Fig. 3). It can be seen from Fig. 2 and 3 that network's total fitness degree and cooperative ratio become steady when system evolves to 200 steps. Now select 50% nodes and make them disappear to simulate the node failure. From the following network's evolution, it's shown that, in single-group network, node failure reduces the network's total fitness degree, but promotes network's cooperative ratio acutely. The reason why the total network fitness degree depresses is that the network's total fitness degree is the sum of all individuals' fitness degree and the numerous nodes' disappearance decreases the scale of social cooperation network immediately. While, the reason why the residual nodes' cooperative ratio rises is that, with the numerous nodes' disappearance, the residual nodes must strengthen cooperation with others to defense the outside competitive environment. For example, in clustered supply chain network, when some enterprises quit the market for some reasons, their original cooperation with the residual enterprises breaks off. Considering the pressure of their own development and the outside competition, the residual enterprises must pay more attention to cooperate with others.

By many simulation experiments, it is found that, in two-group and multi-group cooperation network, node failure can not only decrease the total cooperative fitness degree (It is the same as single-group cooperation network), but also reduce the network cooperative ratio slightly, which is different from single-group cooperation network. Results of simulation in Fig. 4 and 5 shows that, when the interference degree is 50%, node failure reduces cooperative ratio slightly in two-group and multi-group cooperation network. It proves that in more complex social cooperation network, the emergence of node failure can not only bring about the reduction of total network fitness degree, but also decrease network's cooperative ratio in some degree. The reason why the network's cooperative ratio depresses is that the two-group and multi-group cooperation network belong to heterogeneous network, so node failure reduces the scale of social cooperation network and then weaken the heterogeneity of network. The reduction of heterogeneity is bad for cooperation (Santos and

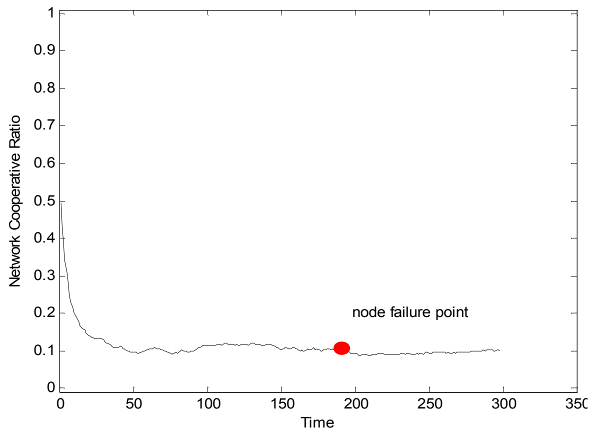


Fig. 4: Influence of node failure on the network's steady cooperative ratio in two-group cooperation network

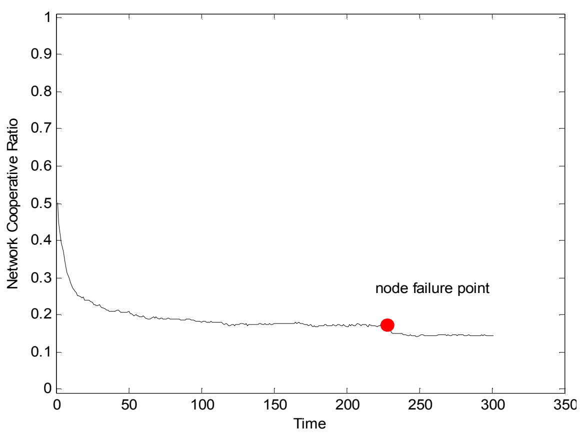


Fig. 5: Influence of note failure on the network's cooperative ratio in multi-group cooperation network

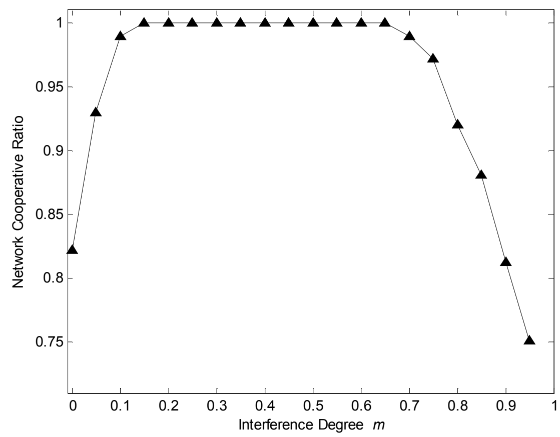


Fig. 6: Influence of *m* on the steady cooperative ratio in single-group cooperation network after node failure

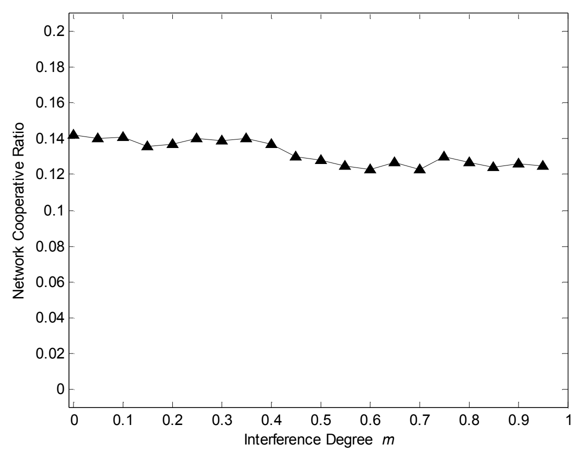


Fig. 7: Influence of *m* on the steady cooperative ratio in multi-group cooperation network after node failure

Pacheco, 2006). Hence, node failure causes the reduction of cooperative ratio in the two-group and multi-group cooperation networks.

**Influence of interference degree on network's cooperative ratio:** From the above discussion, it's found that the node failure increases the cooperative ratio in the single-group cooperation network, but reduces the ratio in the two-group and multi-group cooperation network. In order to conduct a further research on the influence of node failure with different degree on cooperative ratio in different kinds of network, simulation experiments on network's steady cooperative ratio are operated under different interference degree. Figure 6 and 7 show how steady cooperative ratios change with the change of network interference degree in single-group and two-group cooperation network with node failure. The data points in figures refer to the cooperative ratio of network systems reaching stable again after node failure. Every data point is an average of 20 simulation experiments results.

As it shows in Fig. 6, in single-group cooperation network, the node failure promotes the cooperative ratio in single-group cooperation network. Moreover, the interference degree *m* can promote the network cooperation in a wide range of values. However, it doesn't mean the node failure in all degree can promote the cooperative ratio. For example, when the interference degree reaches above 90%, the cooperative ratio is lower than previous.

Different from single-group, all of the node failures can reduce slightly the cooperative ratio with all interference degree in two-group social cooperation network. Through several experiments, it is proved that the influence of the interference degree on the steady cooperative ratio in multi-group social network is similar to the one in two-group cooperation network, so we don't give expatiation again.

**Network's self-repair with node failure:** Although node failure can promote cooperative ratio in

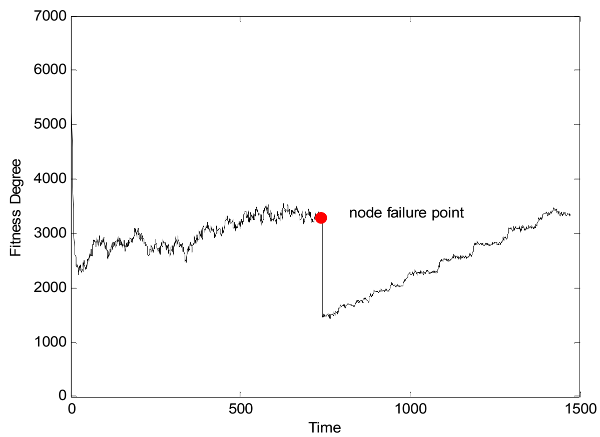


Fig. 8: Network total fitness degree changes with time after introducing the network's self-repair rule

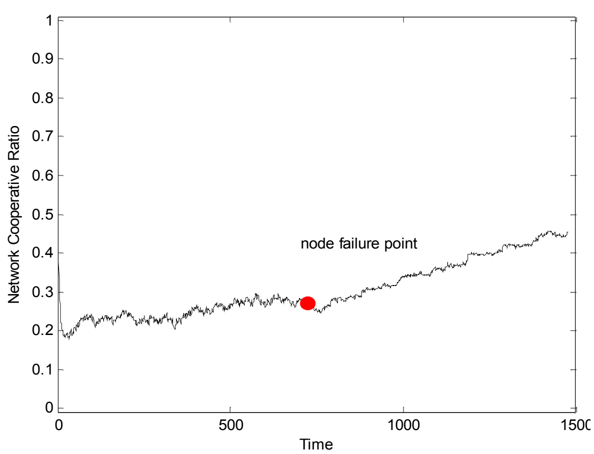


Fig. 9: Cooperative ratio changes with time after introducing network's self-repair rule

cooperation network, it is undesirable. This is because the total fitness degree, namely, the cooperative total benefits, is another important index used to measure the evolution of social cooperation network. The node failure decreases not only the fitness degree of two-group and multi-group cooperation network, but also single-group. Take the cluster supply chain as example, affected by financial crisis, many enterprises go bankrupt. Although the survived enterprises strengthen cooperation with others for rapid recovery, the total benefits of the supply chain decrease with the rising cost of transportation and out of stock. Nodes in real social cooperation network are not static. With the node failure, some original notes disappear and then many new notes come forth subsequently. The relationships between individuals are complex in the realistic world, so single-group cooperation network seldom exists and the majority is two-group and multi-group cooperation network. Therefore, take two-group cooperation network for example in the following to conduct a further research about the influence of mechanism, in

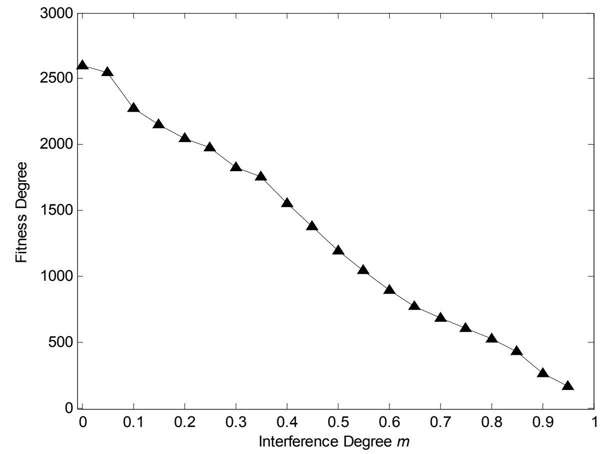


Fig. 10: Relationship between the fitness degree and the interference degree after node failure

which social cooperation network returns to stable through nodes' growth and the priority connection rules, on the total fitness degree and the cooperative ratio.

When the initial cooperation network evolves to be stable, node failure occurs with the interference degree $m = 0.5$. Hence, the total fitness degree decreases suddenly. Subsequently, the continuous participation of new nodes which choose cooperation as initial strategy increases the total fitness degree steadily till the original state before node failure (Fig. 8). The cooperative ratio decreases after node failure, but then increases gradually (Fig. 9), which is different from the situation without the self-repair rule. The reason why the total fitness degree and cooperative ratio can both increase steadily is that the new added nodes make the total number of nodes increase constantly, which increases the total fitness degree. On the anther hand, the initial strategies of the new nodes are all cooperation and they always connected with the reputed existing nodes. When network reaches to be stable again after node failure, new nodes' participation help the terrible-state network.

With node failure, the total fitness degree of social cooperation network decreases, but tends to be stable at the following evolution. Different interference degree results in the different number of disabled nodes, which influences the regained-stable network's total fitness degree to different degrees. The influence is shown in Fig. 10 where very data point is an average of 20 simulation experiments' results. Obviously, with the network being destroyed more and more seriously, the scale of nodes decreases continuously and the original cooperation among disappeared nodes also disappears. Compared with the situation before note failure, the cooperation network's structure and the cooperative relationship between nodes change massively. The obvious change it causes is that the total fitness degree decreases constantly compared with one before note

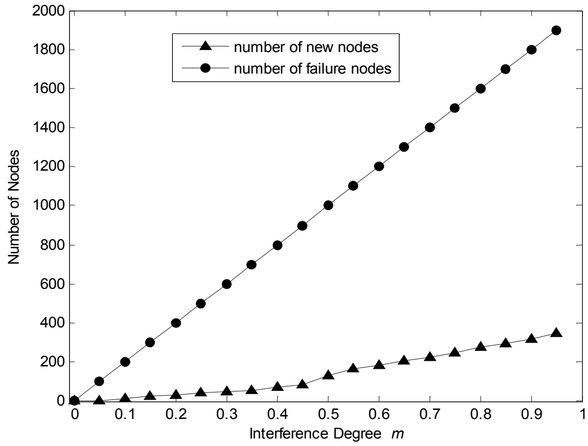


Fig. 11: Number of new added nodes required for network's self-repair change with interference degree

failure. The main reasons for this decrease of fitness degree are the total benefits' decrease by the decrease of nodes' number and the disappearance of relatively mature original cooperation.

Figure 11 shows the comparison with the number of new added nodes required to help the network self-repair to regain the previous fitness degree and the number of disabled nodes which caused by node failure. Every data point in Fig. 11 is an average of 20 simulation experiments' results. It can be seen from Fig. 11 that the more being destroyed of network, the more nodes are required to repair the total benefits back to the previous level before node failure. But in total, the new added nodes are far less than the disabled nodes. The new added nodes don't exceed 20% of disabled nodes. What suggests further in Fig. 11 is that: as the new added nodes always take part in initial game by cooperation and they always choose reputed nodes as their game and study neighbors, so when the destroyed network attain the stable state, the new added nodes taking cooperation to take part in the game break the balance, which makes the development of network transfer to the cooperation. Hence, just adding a few new nodes, the whole network can break stability in a relatively balanced state and tend to cooperation, which finally increases the total fitness degree and cooperative ratio.

## CONCLUSION

Nowadays, financial crisis and terrorist attack break out frequently. So the social cooperation network can be easily affected and cause node failure. In this study, the dynamic evolution model in social cooperation networks with node failures is established on the basis of the social cooperation network structure and the evolutionary game theory. As the structure of the social cooperation network is actually the structure of individuals' cooperation, so the structure of the social cooperation network is destroyed with node failure while the original cooperation is ruined. The results of the simulation experiment show that though node failure debases the total fitness degree in all kinds of social cooperation network, the change of the cooperative ratio show different characteristics. Node failure promotes the cooperative ratio in single-group cooperation network, while it is a negative barrier in two-group and multi-group. When the self-repair rule is further introduced to two-group cooperation network, the total fitness degree and cooperative ratio can both increase rapidly. And it just needs new added nodes, less than 20% of the disabled nodes, to make the fitness degree revive to the previous level. In conclusion, in real world, node failure is bad to the total benefits of the cooperation network, but has different influence on the cooperative ratio in different network. For instance, in the single-group cooperation networks, the cooperative ratio is improved by node failure. Besides, when nodes with emergencies in real social cooperation network becomes partially disabled, the emergence of seldom cooperators can soon make up the loss and improve the total fitness degree and cooperative ratio.

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