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Optimization Characteristics of BA Scale-Free Network and Consistency of Multi-Agent Systems

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ABSTRACT. *The optimization models of BA scale-free network and consistency of multi-agent system are studied. In the case of synchronization optimal network model, a delay robustness optimal BA scale-free network is built. By applying computer simulation, the convergence rates of consistency for multi-agent systems are analyzed. It is shown that the new BA scale-free models can improve the convergence rates and the delay robustness of the network. This research has a great guidance for building a optimization network of multi-agent systems.*

KEYWORDS: *BA scale-free network model; Multi-agent; Consistency; Synchronization optimization; Delay robustness*

1. Introduction

With the rapid development of science and technology, robots are widely used in social life. In recent years, the coordinated control of multi-robot systems based on complex networks has attracted extensive attention of many scholars and experts, and great progress has been made in military tank communication, drones formation, distributed sensors, robot football matches and other fields. It lays a solid foundation for further modeling and analysis of multi-agent system. In the research of multi-robot, according to the autonomy of mobile intelligent robot, the multi-robot system is often regarded as a mobile multi-agent system, and the division of multi-mobile agent system is studied. Cloth cooperation to study the formation control of multi-robot system [1-3]. In the distributed cooperative control of multi-mobile agent system, intelligent individuals adjust the motion state of individuals through the information sharing between neighbors, so that all intelligent individuals can finally get a common purpose, such as the same direction of motion, the same speed, or reach a set point (position consistency), that is, so-called consistency [3]. Therefore, improving the convergence speed of multi-intelligent system unified performance is a research focus in system coordination control at

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present.

The influence of the characteristics of complex network topology on the unified performance of large-scale multi-intelligent systems has achieved some research results in many aspects. For example, Peng Jun et al. proposed an improved scale-free network model in which the newly added nodes take into account both the fitness of the nodes and the saturation of the increased degree of nodes when making preferential connections. Li Zengyang et al. on the basis of BA scale-free network model, considering that the existing node connections are also increasing every time a new node is added, a scale-free network model of internal evolution of BA is proposed. However, due to the sharp increase in the size of the agent and the dynamics of the system, At present, there are still some shortcomings in the research on the unified influence of network structure in multi-intelligent system. In this paper, the influence of scale-free network topology on the consistent convergence rate of multi-agent system is comprehensively analyzed, and the conclusion is verified by computer simulation.

2. Problem description

In 1999, when the models based on stochastic networks were used to depict the World wide Web by Barabasi and Albert, it was found that the connection distribution of World wide Web pages followed the “power law”.The probability that any node is connected to other nodes is proportional to $k^{-\lambda}$, that is $p(k) \propto k^{-\lambda}$, a scale-free network is proposed. Barabasi and Albert further studied the power law based on the scale-free network and found that the real network is formed by the continuous addition of new nodes; the newly added nodes tend to be more connected with those nodes with greater connectivity. The topology characteristics of the scale-free network model are widely existed in real networks. Therefore, the scale-free network model as a more practical multi-mobile agent communication network structure is worthy of our study.

Suppose a multi-agent system consists of N agents, $X_i \in R(i=1,2,\cdots,N)$. We consider this multi-agent system as a BA scale-free network. The network topology diagram shows that $G=(V,E)$, each node in the network system represents an agent. The edges between the pairs of nodes represent state information that can be acquired or perceived by the agents.The adjacency matrix $A=(a_{ij})_{N\times N}$ is used to describe the relationship between nodes and edges, if there is a connection between the node i and the node j , $a_{ij}=1$ otherwise $a_{ij}=0$. If the intelligent group gradually obtains the same velocity vector, or the distance between the two pairs remains stable and there is no collision, the state of all agents is said to eventually become consistent[4].In order to study the consistency of multi-agent systems, we use the Laplace matrix L to describe the relationship between points and edges, $L=D-A$,The values of the elements in the diagonal matrix D are as follows: $D=diag(d_1,d_2,\cdots,d_n)$, d_i is the degree of the vertices. By the consistency algorithm:

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$\dot{x}_i(t) = \sum_{j \in N_i} a_{ij}(x_j(t) - x_i(t))$,the available dynamic equation of motion can be expressed as $\dot{x} = -Lx$,a function of the energy $\varphi(\delta) = \|\delta\|^2 = \sum_{i=1}^{n} \delta_i^T \delta_i = \delta^T \delta$,and its derivative can be obtained $\dot{\varphi} = -2\delta^T L\delta \le -2\lambda_2 \delta^T \delta = -2\lambda_2 \varphi$, ie $\varphi_{(t)} \to e^{-2\lambda_2 t}$, $\delta = [\delta_1, \delta_2, \cdots, \delta_n]a$, $\delta_i = x_i - \alpha$.[2-4]Therefore,the second minimum eigenvalue λ_2 of the Laplacian matrix in the multi-agent network system can be used to measure the convergence speed of the consistency algorithm, and the larger the network convergence speed, the faster the communication line and communication equipment of the actual network. Due to other reasons such as the actual network communication lines and communication equipment, there is communication delay in information transmission between multiple intelligent individuals. Therefore, it is more practical to discuss a consistent algorithm with communication delay, and the communication delay is satisfied $\tau < \frac{\pi}{2\lambda_n}$, When the system is able to achieve an average consistency. In this paper, the maximum eigenvalue λ_n of Laplacian matrix L as a delay robustness index directly affects the range of network allowable delay.

Taking the BA network model as an example, the influence of the degree-negative correlation of the scale-free network on the consistency of the multi-agent system is studied. (As a comparison, the BBV network model is used as an example to study the degree of negative correlation of the network) After the average distance of the scale network model and the relationship between the average cluster coefficient and the convergence of the multi-agent system, the influence of the change on the convergence speed of the optimization consistency is obtained. Based on this research, in order to make all agents quickly achieve consistency, we are working to find a BA scale-free network model with the best convergence speed, and then construct an ideal large-scale multi-agent dynamic network structure. The problem studied in this paper is the consistency between the optimized BA scale-free network model and the multi-agent system. The innovation is that when constructing the BA scale-free network, each new node added is not connected to the connected network. There are nodes, but there are choices: (1) The nodes with the highest algebraic connectivity of the network obtained after the connection are connected. The resulting BA scale-free network is called the synchronization optimization based on the BA scale-free network. The network model, verified by simulation analysis, the consistency convergence speed of the synchronous optimal network is significantly better than that of the BA scale-free network; (2) the node with the smallest eigenvalue of the Laplacian matrix of the network obtained after the connection and connection Connected, the resulting network is called the delay robust optimal network model. Through simulation analysis, the delay robustness of the network model is significantly better than that of the BA scale-free network. This is to improve the multi-agent system. Performance has great guiding significance.

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3. Optimized BA scale-free network model

3.1 Synchronous optimal network model based on BA scale-free network

On the basis of the BA scale-free network, each new node added is not connected to the existing node with a large degree of connectivity, but is preferentially connected to the node with the largest algebraic connectivity of the network after being reconnected. The BA scale-free network can further improve the consistency convergence speed of the network. The algorithm steps are as follows:

(1) Growth: Suppose a network starts with m_0 nodes, each time adding a new node, and connecting the newly added node to m existing nodes $(m << m_0)$.

(2) Synchronous priority connection: When the new node is connected to the existing nod i , the synchronization performance of the constructed new network is optimized, that is, the second small feature value λ_2 of the Laplacian matrix L of the new network is maximized.

After t steps, a network model with optimal synchronization performance with $N = t + m_0$ nodes and mt edges is generated. When N tends to infinity, the second small eigenvalue $\bar{\lambda}_2$ of the Laplacian matrix L of the network tends to be a constant.

3.2 Time-delay robust optimal network model based on BA scale-free network

Based on the BA scale-free network, the consistency of the multi-agent system is studied. It is not only considering the consistency convergence speed of the network, but also considering the communication delay existing in the network. This section is based on the BA scale-free network model. Each time a new node is added, the node is connected to the node that forms the minimum value of the maximum eigenvalue of the Laplacian matrix of the new network. The delay of the network model is robust. The performance is obviously better than the BA scale-free network model. The algorithm steps are as follows:

(1) Growth: Suppose a network starts with m_0 nodes, each time adding a new node, and connecting the newly added node to the existing nodes m , $(m << m_0)$.

(2) Priority connection: When the new node is connected to the existing node i , the delay robustness of the constructed new network is optimized, that is, the maximum eigenvalue λ_n of the Laplacian matrix L of the new network is minimized.

After t steps, a network model with the largest allowable delay of $N = t + m_0$ nodes and mt strips is generated. When N tends to infinity, the maximum eigenvalue $\underline{\lambda}_n$ of the Laplacian matrix L of the network tends to be a constant.

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4. Simulation analysis

4.1 Simulation Analysis of Synchronous Optimal Network Model Based on BA Scale-Free Network

The relationship between the network size and the maximum value of λ_2 of the synchronous optimal network model based on the BA scale-free network is analyzed. Firstly, according to the construction algorithm of the synchronization performance optimal growth network model, starting from a network withnodes, each time step adds a new node, which is guaranteed under the premise that the synchronization performance of the constructed new network is optimal. The second smallest eigenvalue of the Laplacian matrix L of the new network obtained after the connection is the largest, and the new node is connected to the existing m nodes. After t steps, a network model with the best synchronization performance of $N = t + m_0$ nodes is obtained. Taking the network scale N as the abscissa, the maximum value of the algebraic connectivity λ_2 is the ordinate, and the simulation is plotted. As can be seen from Figure 1, we analyze these three cases, $m_0 = m = 3,5,7$ that is, the maximum number of algebraic connectivity λ_2 in these three cases. As the network scale increases, the value shows a growing trend. That is, the larger the network size, the greater the convergence speed of consistency. And for the same network scale, the maximum value of the algebraic connectivity increases with the increase of $m_0 = ma$,that is, the better the synchronization performance of the network, the greater the convergence speed of consistency. The proposed model is very helpful for optimizing the consistency convergence speed of scale-free networks.

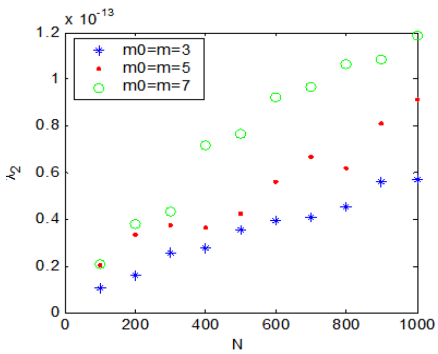

Figure. 1 Relationship between the network size N and the maximum value of λ_2

4.2 Simulation Analysis of Time Delay Robust Optimal Network Model Based on BA Scale-Free Network

The relationship between the network size and the minimum value of λ_n of the

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delay robust optimal network model based on BA scale-free network is analyzed. Considering the existence of communication delay in the actual network, and λ_n which is the maximum value of the Laplacian matrix eigenvalue is a performance index to measure the robustness of delay, therefore, based on the BA network model, we propose the time-delay robustness optimal network model. Firstly, we construct the algorithm based on the time-delay robustness optimal growth network model. Firstly, according to the construction algorithm of the delay-optimized growth network model, starting from a network with nodes, a new node is added in each time step. Under the premise that the time delay robustness of the new network formed is optimal, the maximum eigenvalue of Laplace matrix L of the new network obtained after connection is guaranteed to be the minimum, and the new node is connected to the existing nodes. After t steps, a network model which has $N = t + m_0$ nodes with optimal delay performance and robustness is obtained. Taking the network scale N as the abscissa, the minimum value of the maximum eigenvalue of the Laplacian matrix L is the ordinate, and the simulation is plotted. As can be seen from Figure 2, we analyze these three cases, namely in these three cases

$m_0 = m = 3,5,7$. As the network scale increases, $\underline{\lambda}_n$ shows a growing trend, and with the increase of $m_0 = m$, the growth trend becomes more stable, that is, the larger the network scale, the worse the delay of the network is. Under the condition of the same network scale, $\underline{\lambda}_n$ increases with the increase of $m_0 = m$, that is, the larger $m_0 = m$ of the network, the worse the time delay robustness.

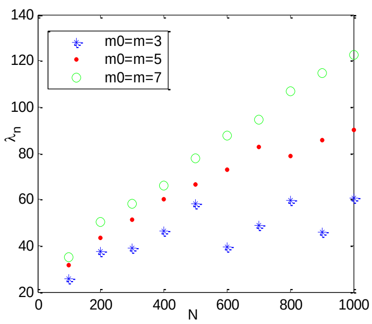

Figure. 2 The relationship between network size N and the minimum value of λ_n

5. Performance Analysis of Optimized Network Model

On the basis of the BA scale-free network model, starting from a network with m_0 nodes, one node is added per time step, and when the newly added node is connected to the existing nodes, two cases are proposed respectively:

The second small eigenvalue of the Laplacian matrix of the connected network is

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guaranteed to be the largest, so the synchronous optimal network model based on BA network is obtained.By comparing with the consistent convergence time of BA network model, it can be seen from figure 3 that data1 represents the consistent convergence time curve of BA scale-free network model, and data2 represents the consistency convergence time of the synchronous optimal network model based on BA scale-free network. Under the same network scale, the consistency convergence time of the synchronous optimal network model tends to be smaller than that of the BA network model, that is, the consistency convergence speed of the network model is higher than that of the BA network model.

Because of the communication delay in the real network, the optimal network model based on BA scale-free network is obtained under the condition that the maximum eigenvalue of the Laplace matrix of the network obtained after connection is guaranteed to be the minimum.

By comparing with the maximum allowable communication delay of the BA network model, as shown in Figure 4, data1 and data2 represent the maximum communication delay allowed by the BA scale-free network model and the time-delay robust optimal network model based on BA scale-free network. As can be seen from the figure, the maximum communication delay allowed by the delay robust optimal network model is significantly higher than the BA network model, when the network scale is the same, that is, the delay robustness of that network is better than the BA network model.

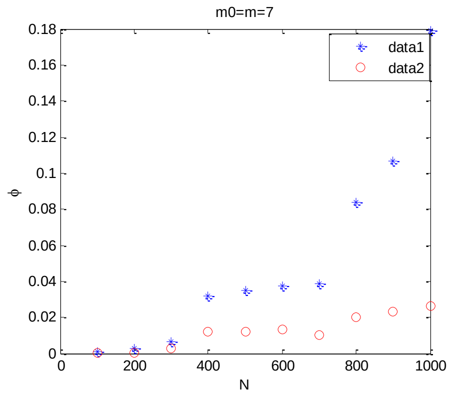

Figure.3 Relationship between network scale and consistency convergence time of BA scale-free network model and BA-based synchronous optimal network model

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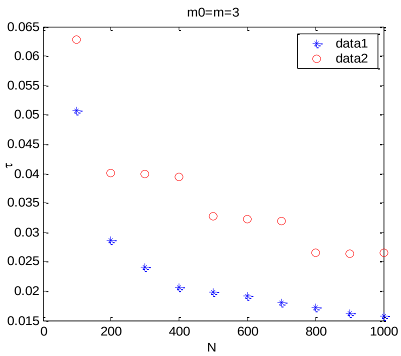

Figure. 4 Relationship between the network scale of the BA scale-free network model and the BA network-based delay robust optimal network model and the maximum communication delay allowed by the network

6. Summary

In this paper, based on the topology structure of BA scale-free network model, two optimization network models are proposed, according to the growth and optimal connectivity of the actual network: the synchronous optimal network model based on BA scale-free network and the time-delay robustness optimal network model based on BA scale-free network.The simulation analysis proves that the consistency convergence speed of the synchronous optimal network model is better than that of the BA network model, and the maximum communication delay allowed by the delay robust optimal network model is also larger than that of the BA network model. This study verifies that the uniform convergence speed of multi-agent systems can be improved by optimizing the topology of scale-free networks. This research has great guiding significance for designing and constructing a high-performance multi-agent network model.

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