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Pinning synchronization with low energy cost

Fuzhong Nian [a,b], Qianchuan Zhao [b,*]

[a] School of Computer & Communication, Lanzhou University of Technology, Lanzhou 730050, China
[b] Department of Automation, Tsinghua University, Beijing 100084, China

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ABSTRACT

The pinning synchronization on complex networks with low energy cost was investigated. Two basic problems were considered, in this paper. One is how to achieve synchronization on complex network with weak coupling. Another is how to reduce the energy cost in the process of achieving and keeping synchronization. On the other hand, for a good pinning strategy, the synchronizing speed should also be ensured. In this paper, a switching pinning strategy was proposed to enhance the synchronizing speed. And from the point of view of energy saving, some selected links were strengthened. Theoretical analysis and simulations on different complex networks indicate that the proposed pinning strategy is effective. Compare with conventional existing method, the superiority of our method is significant.
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1. Introduction

Synchronization is a ubiquitous in nature. It plays a very important role in many different fields such as biology, ecology, climatology, sociology, technology, or even in arts [1–3]. Especially, synchronization on large networks of interconnected dynamic systems has been a hot topic [4–13]. To realize network synchronization, a general method is adding designed controllers on every node of networks to achieve synchronization. However, the real-world networks generally have a large number of nodes. Therefore, it is usually difficult to control a complex networks by adding the controllers to all nodes. To reduce the number of the controllers, Grigoriev et al. proposed a pinning control to solve the problem [14].

Recently, many pinning schemes have been proposed in different networks [13,15–30]. Certainly, the nodes need to add controller should as little as possible. But how many controllers need to add at least? And how much coupling strength should be for a network with fixed structure? Zhou et al. proposed an approximate method for estimating the detailed number of pinning nodes and the magnitude of the coupling strength for a given general complex dynamical network [31]. In fact, before Zhou's method, Chen et al. has given a good method which only a single controller needs to pin [32]. However, it requires a very large coupling strength in general, which may not be very practical.

In fact, for the fixed pinning schemes which mentioned above, to achieve synchronization, the coupling must be strong enough [33]. As we know, in practice, we cannot ensure all networks with strong coupling. And on the other hand, from the point of view of energy saving, the active controllers should as little as possible, the best is only one controller is working at any time. And, at the same time, the coupling strength should be reduced as weak as possible. Therefore, how to achieve synchronization on complex networks with weak coupling is an important problem. To solve the problem, in this paper, we designed a switching pining scheme to achieve synchronization on complex network with weak coupling.

The rest of the paper is organized as following. In Section 2, switching pinning synchronization with fixed coupling strength. Is investigated, and the theoretical analysis and simulations are given in this section. Then, in Section 3, we

* Corresponding author. Tel.: +86 10 62783612; fax: +86 10 62796115.
E-mail addresses: gdnfz@lut.cn (F. Nian), zhaoqc@tsinghua.edu.cn (Q. Zhao).

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investigate the switching pinning synchronization with adaptive enhanced coupling strength, the theoretical analysis and computer simulations are given too. Finally, conclusions are given in Section 4.

2. Switching pinning synchronization with fixed coupling strength

2.1. Theoretical analysis

Except for topology of network, two factors are very important to synchronization of complex network. One is how many nodes need to control. Certainly, it is better to reduce the nodes need to control. Another is how much the coupling strengths between two connected nodes should be. In practice, the bigger the coupling strengths are, the faster the synchronization is achieved. However, enhancing coupling strength means use of more energy. Thus, enhancing coupling strength at all nodes may not be an economical strategy.

The conventional pinning strategy is adding the designed controllers to part of selected nodes, and the nodes to be controlled are fixed in all time. These strategies really can realize the synchronization. However, what is the most economical scheme? Until today, few of them consider the cost of energy. From the point of energy saving, we have no choice but to consider the cost of energy. In this paper, the nodes need to control are selected dynamically at each time interval. To save the energy of whole network, the coupling strength also were enhanced adaptively.

Firstly, the pinning nodes have not to be fixed. The reason is that along with the evolution of the system, the original selected pinning nodes may be not the best selection. Thus, if the modification were not made in time, means use of more energy or more time, sometimes, both of them would be wasted. How to resolve the problem? Adaptive switching pinning synchronization on complex network is proposed in this paper.

The complex network with adaptive switching pinning controllers is described as follows:

$$\dot{\boldsymbol{X}}_i = \boldsymbol{F}(\boldsymbol{X}_i) + \sum_{j=1, j\neq i}^{N} \mathbf{C}_{ij}\boldsymbol{\Omega}(\boldsymbol{X}_j - \boldsymbol{X}_i) + k_i\boldsymbol{u}_i, \quad (i = 1, 2, \ldots, N,\ k_i \in \{0, 1\}). \tag{1}$$

Here, $\boldsymbol{X}_i$ is the state vector of ith node. The constant matrix $\boldsymbol{\Omega} \in R^{n\times n}$ is the inner coupling matrix; $\mathbf{C}_{ij}$ is the weighted coupling matrix, $\mathbf{C}_{ij} = \mathbf{A}_{ij}\mathbf{P}_{ij}$, where $\mathbf{A}_{ij}$ is the binary adjacency matrix and $\mathbf{P}_{ij} > 0$ is the coupling strength from node j to node i if they are connected. In unweighted networks, $\mathbf{P}_{ij} = \mathbf{I}$ is uniform for all links.

To achieve synchronization on network (1), the designed controller is added to every node. But it is not a good scheme. In fact, only a small fraction δ $(0 < \delta < 1)$ of the nodes in network (1) need to add the controller. This is the pinning synchronization. For simplicity, suppose the first $l = \lfloor \delta N \rfloor$ nodes are selected to add the controller. Where $l = \lfloor \delta N \rfloor$ represents the integer part of the real number δN. Thus, the pinning controlled network can be described by

$$\begin{cases} \dot{\boldsymbol{X}}_i = \boldsymbol{F}(\boldsymbol{X}_i) + c\sum\limits_{j=1, j\neq i}^{N} A_{ij}\boldsymbol{\Omega}\boldsymbol{e}_j + \boldsymbol{u}_i, & i = 1, 2, \ldots, l, \\ \dot{\boldsymbol{X}}_i = \boldsymbol{F}(\boldsymbol{X}_i) + c\sum\limits_{j=1, j\neq i}^{N} A_{ij}\boldsymbol{\Omega}\boldsymbol{e}_j, & i = l+1, \ldots, N, \end{cases} \tag{2}$$

where, c is the fixed coupling strength.

Consider an isolated node, the dynamical system can be denoted by:

$$\dot{\boldsymbol{S}} = \boldsymbol{F}(\boldsymbol{S}). \tag{3}$$

Here, $\boldsymbol{S}$ is the solution of an isolated node dynamical system. It may be an equilibrium point, a periodic orbit, or even a chaotic orbit.

The complex dynamical network (2) is said to achieve synchronization (under control) asymptotically if we can find a control input such that

$$\boldsymbol{X}_1(t) \to \boldsymbol{X}_2(t) \to \cdots \to \boldsymbol{X}_N(t) \to \boldsymbol{S}(t). \tag{4}$$

Here, $X \to Y$ denotes X tends to Y infinitely, thus, the expression (4) is equivalent to:

$$\lim_{t\to\infty} \|\boldsymbol{X}_i(t) - \boldsymbol{S}(t)\|_2 = 0, \quad (i = 1, 2, \ldots, N). \tag{5}$$

The object is achieving synchronization on the network. To achieve the synchronization of network (2), the controllers should be added on a small fraction δ $(0 < \delta < 1)$ of the nodes of network. The conventional pinning method is to apply control on a fixed small fraction of selected nodes. For example, the first l nodes are selected to pinning. It really can achieve the goal. However, it may not the best strategy. Because the achieving synchronization is a dynamic process, and all the states would change with time going, thus the errors also would change with time, and the pinning nodes should be selected dynamically according to the changes. In the following, the pinning nodes were re-selected according to the latest errors at the beginning of each time interval.

Consider node $\boldsymbol{X}_i$ and its neighbor $\boldsymbol{X}_j$ $(j \in M_i)$:

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