



Cluster synchronization for nonlinearly time-varying delayed coupling complex networks with stochastic perturbation via periodically intermittent pinning control



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ABSTRACT

This paper investigate the mean square exponential cluster synchronization of a class complex networks with nonlinear hybrid time-varying delays and stochastic noises via periodically intermittent pinning control. To be more practical, the network topology can be directed and the time delay is assumed to be time-varying. Based on the Lyapunov stability theory, stochastic analysis theory and linear matrix inequalities(LMI), the sufficient conditions are derived to guarantee the mean square exponential cluster synchronization. Furthermore, our results can cover and extend the related ones in existing literatures. Some numerical simulations are provided to show the effectiveness of our theoretical results.

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1. Introduction

Complex networks are ubiquitous around the real world, such as the World Wide Web, the power grids, transportation networks, biological networks, and the economic networks, see [1–5] and references therein. Since complex networks have numerous applications in real world, many studies have been made on complex networks and related subjects. For instance, the problem of extended dissipativity-based state estimation for discrete-time Markov jump neural networks is investigated in [6]. Synchronization, an important and interesting group behavior of networks, has been raised much concern in various fields in recent decades, including communication, engineering, physical science, mathematics and sociology. Over the past decades many different kinds of synchronization protocols have been studied, such as complete synchronization [7–10], lag synchronization [11,12], finite-time synchronization [13], cluster synchronization [14] and so on. Among those synchronization types, the investigations on cluster synchronization have been received more and more attentions. In the other hand, community behaviors or cluster actions always appear among nodes in complex dynamical networks. Therefore, it is necessary and meaningful to study the cluster synchronization due to its universality compared with the complete synchronization. Cluster synchronization means that all nodes in the networks split into several groups, and the nodes belong to the same group have the same dynamical behaviors, while the nodes in different ones show different dynamical behaviors. Taking into consideration of its significance, many works have been done by a lot of researchers from various fields. Ma et al. [15] and Liu and Chen [16] studied the cluster synchronization of coupled identical systems. In [17,18], the authors considered about cluster synchronization in networks of coupled nonidentical dynamical systems, and obtained some conditions guaranteeing cluster synchronization.

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Generally, as shown above, the investigations of cluster synchronization mainly focused on the networks that had the same outer-coupling strength and the inner-couplings were linear. But in the practical application, obstructed by some kinds of factors, the inner-coupling of a network is not usually linear, and at the most time, it is the nonlinear-coupling. In other words, sometimes the state variable $x_i(t)$ may be not easy to be observed, but the $g(x_i(t))$ can be obtained easily. For example, the model in [19] of cluster synchronization of nonlinearly-coupled complex networks is described as

$$\dot{x}_i(t) = f_{\mu_i}(x_i(t)) + c \sum_{j=1}^N a_{ij} \Gamma g(x_j(t)), \quad i = 1, 2, \dots, N,$$

where $g(x_j(t))$ represents the nonlinearly-coupled vector function. As we know, time delays are crucial components in a network, usually caused by the communication delays among nodes, that is to say during the exchange process there are always exist the time-delays. Also there have been a lot of works dealing with synchronization problems with delays, see [13,20–29]. For example, in [13], the authors focused on the problem of finite-time $\mathcal{H}_\infty$ synchronization for complex networks with time-varying delays and semi-Markov jump topology. The complete synchronization problems for linearly coupled networks with delays by pinning a simple aperiodically intermittent controller was investigated in [20] and some critics were obtained related to time delays or unrelated to time delays. However, the model is linearly-coupled in [20], and it is may formidable to extend it to the general case, which means the nonlinearly-coupling is more general than the linearly-coupling. Moreover, many works about the delay are related with the internal delay or coupled delay, few of them are about the two types combined. In [21], the internal delay is investigated, as well as Li and Chen [22] studies the coupling delay synchronization and some criterion are obtained. On the other hand, it is well known that noise is ubiquitous in practical environments, therefore it is necessary to concern about the cluster synchronization for dynamical system with noises. In [23], the stochastic noise is introduced, but the coupling between nodes is linear and the internal delay is unconcerned. The similar case is shown in [24], and dynamical behaviors contain time-varying delays and the noises are also contained, while the system model is linearly-coupled. In [25], the cluster synchronization in nonlinearly coupled delayed networks was investigated, in which the delay is time-varying, and some critics of realizing the cluster synchronization are obtained. But the internal delays and the noises are not included. In addition, there are few works about those three cases. From our perspective, it will be better to combine with internal delay and nonlinearly delay coupled as well as noise. And to be more practical, the delays are all time-varying.

Generally speaking, it is difficult to reach the synchronization by themselves for a class of complex dynamical networks. In order to synchronize a network, a variety of control schemes have been designed, such as pinning control [30–32], impulsive control [33], cost dynamic control [34] and sampled-data control [35,36]. Chen et al. introduced a single controller to synchronize the network in [30], in which the controller is only added to a node. In [31], the authors investigated the cluster synchronization by pinning control, which further explains the significance and wide range of applications of pinning control. In [32], authors designed a pinning controller for cluster synchronization of complex dynamical networks with semi-Markovian jump topology, which push the studies of pinning control for cluster synchronization further. Cai et al. [33] investigated a class dynamical complex networks with internal delays by the impulsive control and some conditions are obtained. Synchronization problem of a complex dynamical network with randomly switching topology was studied by decentralized guaranteed cost dynamic control in [34]. And the authors applied delayed sampled-data controller to synchronize a complex dynamical network with coupling time-varying delays in [35]. Recently, periodically intermittent control has exerted a tremendous fascination on many fields, such as process, ecosystem management, and communication, which means that it is composed of “work time” (with control) and “rest time” (without control). Compared with the continuous control method, the periodically intermittent control has greater benefits of efficiency and practicability, that is to say, it is not necessary to control nodes all the time. The periodically intermittent control of complex dynamical networks with time-varying delays was investigated in [37]. In [38], the authors did some works about the cluster synchronization by periodically intermittent pinning control, in which the nodes were identical and all had internal time-varying delays. By using pinning periodically intermittent controllers, combined with delay differential inequalities, some conditions for cluster synchronization were gained. In order to carry the point to save energy, it was only pinning one node in different clusters and the other nodes remain uncontrolled among the work time, while in the rest time all nodes need not to be controlled. But the model in [38] is linear coupling and it is not concerned the stochastic noises.

Inspired by the above analysis, this paper further studies the cluster synchronization for delayed complex networks based on the periodically intermittent pinning control. Nonlinearly and time-varying delayed coupling of network are introduced, as well as the internal time-varying delay, and all nodes in the network are supposed to be affected by communication noises, which is realistic in practice. What is more, the dynamical behaviors are concerned discrepant in different clusters. In other words, nodes in the same cluster share the common dynamical behaviors, while in different clusters their dynamical behaviors are different. We also control one node in each cluster in work time, while in rest time no nodes over the whole network need to be controlled. In addition, in many practical systems it is unrealistic to assume all the nodes to be cooperative. Obviously, cooperative and competitive dynamical systems are more actuality in the real-world. Meantime, we also stipulate the delays are all time-varying and bounded. In other words, the delay is the continuous bounded function

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