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Research Article

Distributed synchronization control of complex networks with communication constraints ☆

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ABSTRACT

This paper is concerned with the distributed synchronization control of complex networks with communication constraints. In this work, the controllers communicate with each other through the wireless network, acting as a controller network. Due to the constrained transmission power, techniques such as the packet size reduction and transmission rate reduction schemes are proposed which could help reduce communication load of the controller network. The packet dropout problem is also considered in the controller design since it is often encountered in networked control systems. We show that the closed-loop system can be modeled as a switched system with uncertainties and random variables. By resorting to the switched system approach and some stochastic system analysis method, a new sufficient condition is firstly proposed such that the exponential synchronization is guaranteed in the mean-square sense. The controller gains are determined by using the well-known cone complementarity linearization (CCL) algorithm. Finally, a simulation study is performed, which demonstrates the effectiveness of the proposed design algorithm.

1. Introduction

In the past a few decades, there has been a large number of results reported on the complex networks due to their successful applications in various fields such as the Internet, multi-agent systems, World Wide Web, sensor networks and biological networks, see [1–5] and the references therein. In particular, the synchronization problem has attracted rapidly increasing interests and many efficient approaches have been presented to solve the synchronization problem of complex networks. For example, in [6], a unified approach was proposed to the analysis of the synchronization for complex networks, where both the nonlinear and the nonlinear node dynamics scenarios were considered. The explicit convergence rate was specified with a much simpler form. In [7], the controlled synchronization problem was studied for the complex networks with random delayed information exchange. In particular, a binary stochastic variable was utilized to model the randomly occurring delay phenomena. Some delay-dependent synchronization conditions have been obtained and controller design was also proposed. Recent advances on the synchronization of complex networks can be found in [8–12].

In some practical applications of synchronization systems, how to design the systems for special signal transmission channels has become a critical issue. For example, the network-based synchronization control of delayed neural networks was discussed in [13], and the main concern is the packet dropouts and time-varying communication delay. A logic data processor and a logic zero order hold were proposed in the master–slave synchronization framework and the closed-loop synchronization error system was modeled as a time-delay system. By using the Jensen's inequality approach, some synchronization criteria were proposed such that the synchronization error system is exponentially stable. Recently, the stochastic sampled-data synchronization control of complex dynamical networks with control packet loss was investigated in [14], where a novel Lyapunov functional with triple integral terms was constructed and sufficient conditions were proposed such that the dynamical network was exponentially mean-square stable. It is worth pointing out that the above results are only applicable for the complex networks with wired communication. Note that a wireless communication system can provide more flexibility in system design and ease in installation, which is more suitable than the wired control systems in many industrial applications. Compared with the wired communication systems, the transmission power of wireless node should be carefully scheduled as the wireless node

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usually equipped with battery and replacing the battery is difficult. To save the constrained power in wireless networked system, the measured data cannot be transmitted directly, i.e., the communication is constrained. To the best of our knowledge, the synchronization control of complex networks with communication constraints has not been fully investigated yet and still remains challenging. This motivates the present study.

Based on the above observations, we consider the distributed synchronization control of complex networks with communication constraints. In the considered systems, the local controller is able to communicate the neighboring ones according to certain topologies. To satisfy finite power budget, only partial components of the local information vector are quantized and transmitted to the neighboring controller and a measurement size selection policy is proposed to achieve this goal. Moreover, a time-varying communication schemes are introduced such that the controllers are communicating intermittently. A unified switched system model is derived for the closed-loop system, and the stability and stabilization conditions are presented such that the synchronization error system is exponentially stable. Finally, a simulation study is given to show the effectiveness of the proposed controller design algorithm.

The contributions of this paper are summarized as follows:

(1) The synchronization control of complex networks with wireless communication is first addressed, and it could provide more advantages than that of the wired based one [13] and [14].
(2) The two strategies, i.e., measurement size reduction and transmission rate reduction are introduced simultaneously to alleviate the communication constraint problem.
(3) Some interesting results are obtained in this work, e.g., the exponential decay rate of the synchronization error system is critically dependent on the scheduling frequency of measurement selection strategy.

Notations: R^n denotes the n dimensional Euclidean space. The superscript "T" is used to stand for the matrix transposition. $\mathbb{E}\{\bullet\}$ and $\Pr ob\{\bullet\}$ are the mathematical expectation and probability of the event "$\bullet$", respectively. The symbol "$*$" is used to describe the symmetry of a matrix and $\otimes$ is denoted as the Kronecker product. We use $\mathrm{diag}\{\cdots\}$ to describe the block-diagonal matrix and *trace* (W) is the trace of matrix W. I and 0 represent the identity matrix and zero matrix with appropriate dimensions.

2. Problem formulation

The considered complex network is depicted in Fig. 1, where the purpose is to design a set of controllers such that the follower can track the leader. Different from the existing results, the controller is not working alone, instead, they can communicate with each other via the wireless communication network.

Consider a discrete-time complex network with N nodes and the p-th node dynamics is described as

$$\begin{cases} x_p(k+1) = Ax_p(k) + f(k, x_p(k)) + \sum_{q=1}^{N} b_{pq} T x_q(k) + E_p w_p(k) + u_p(k) \\ z_p(k) = L x_p(k) \end{cases} \tag{1}$$

where $x_p(k) = \left[x_{p1}^T(k) \ \cdots \ x_{pn}^T(k) \right]^T \in \mathrm{R}^n$ is the state vector of the p-th node, the $z_p(k) \in \mathrm{R}^p$ is the interested performance vector. $w_p(k) \in \mathrm{R}^q$ is the unknown disturbance, which is assumed to belong to $l_2[0, \infty)$. A, E_p and L are some constant matrices with appropriate

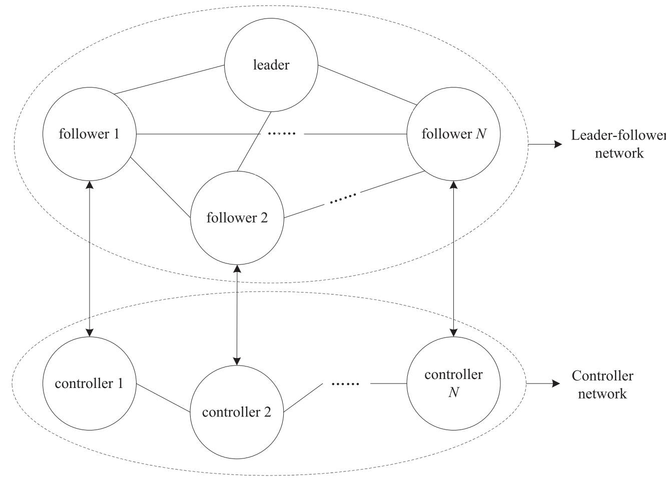

Fig. 1. The structure of considered complex network.

dimensions. $T = \mathrm{diag}\{t_1, t_2, \ldots, t_n\}$ is an inner-coupling matrix with $t_p = 1$ for the p-th subsystem with $t_p = 0$ for $q \neq p$, which means that two coupled nodes are connected through their p-th state variables. $B = \left[b_{pq} \right]_{N \times N}$ is the coupling configuration matrix of the network with $b_{pq} \geq 0, p \neq q$. This matrix is usually assumed to be symmetric and satisfies

$$\sum_{q=1}^{N} b_{pq} = \sum_{p=1}^{N} b_{qp} = 0, \quad p = 1, 2, \ldots, N \tag{2}$$

In system (1), $f : \mathrm{R}_{[0,\infty]_{\times \mathrm{R}^n}} \to \mathrm{R}^n$ is a smooth nonlinear vector-valued function, and it is assumed to satisfy [8]

$$\| f(x) - f(y) \| \leq \| U(x-y) \| \tag{3}$$

where U is a constant matrix with appropriate dimensions.

Let $e(k) = x_p(k) - s(k), p = 1, 2, \ldots, N$ be the synchronization errors, where $s(k) \in \mathrm{R}^n$ is the state vector of the leader node with the dynamics as

$$\begin{cases} s(k+1) = As(k) + f(k, s(k)) \\ z(k) = Ls(k) \end{cases} \tag{4}$$

where $z(k) \in \mathrm{R}^p$ is the performance vector. Introducing the zero term $\sum_{p=1}^{N} b_{pq} Ts(k)$, and considering (2) and (4), the error dynamics of the above complex network can be written as

$$\begin{cases} e_p(k+1) = Ae_p(k) + g(k, e_p(k)) + \sum_{q=1}^{N} b_{pq} T e_q(k) + E_p w_p(k) + u_p(k) \\ \tilde{z}_p(k) = L e_p(k) \end{cases} \tag{5}$$

where $\tilde{z}_p(k) = z_p(k) - z(k)$ is the performance error, $g(k, e_p(k)) = f(k, x_p(k)) - f(k, s(k))$.

Remark 1. In this paper, the considered system (1) is designed to track the leader system (4), where the state of system (4) has n dimension. Hence, all the state of each node is assumed to be with n dimension. The system dimension might be different in some scenarios, and such a heterogeneous complex network has been studied in the framework of output regulation [15]. We only focus on the identical node case and the synchronization control of heterogeneous complex network will be left as our future work.

Due to the fact the controllers can communicate with each other through the wireless communication network, some effective energy-efficient transmission protocols should be used to reduce the communication load. It is well known that in wireless networks, most of power is consumed during the transmission process, and more power can be save if one reduce the transmission rate and

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