Exponential Stability Criteria for Feedback Controlled Complex Dynamical Networks with Time Delay

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Abstract: Time delays commonly exist in the real world, so it is necessary to study the control of such systems with time delay. In this work, we control complex dynamical networks with time delay onto their homogeneous stationary state by applying local feedback injections to a small fraction of nodes. Both asymptotical stability and exponential stability criteria are derived by Lyapunov’s direct method. The efficiency of the derived results was illustrated by simulation study.

Key words: time delay; stability; Linear Matrix Inequality; complex dynamical network

1 Introduction

Complex networks exist in various fields of real world[1–6] such as in the Internet, the world Wide Web (WWW), electric power grids, etc., and thus become more and more important in our daily life. A complex network consists of a large number of nodes and the connections between them. These nodes can have different meanings in different situations, such as computers, microprocessors, papers, companies, and so on. The nature of complex networks is their complexity, including topological structure, dynamical evolution, connection or node diversity and meta-complication, etc..

Traditionally, scientists thought that the connections between the elements of real networks could be described by regular topological structures[7–13], such as chains, grids, lattice and full-connected graphs. Complex networks were studied by graph theory later, for which the basic theory was introduced by Erdős and Rényi [14, 15] as the ER (Erdős-Rényi) random model, which has dominated the mathematical research of complex networks for nearly half a century. Recently, Watts and Strogatz introduced small-world networks [1, 16, 17] to describe the transition from regular networks to random ones. The small-world effect is that large clusters and short average path length exist simultaneously. With a number of demonstrations, scientists discover that a number of real-life networks have scale-free feature, which is first introduced by Barabási and Albert [3, 9]. The connectivity of these networks exhibit power-law distribution.

In the last decade, the synchronization of chaotic coupled networks has attracted much attention of researchers in this field[18-21]. Small-world effect and scale-free property play critical roles in complexity[4, 22–24]. Due to the inhomogeneity, the control problem for scale-free dynamical networks was usually investigated by applying local linear feedback injections to a small fraction of network node [6, 7, 23]. Time delays commonly exist in the world [25–27], some of which can be ignored and some others must be taken into account, such as in long-distance communication and traffic congestions. So it is necessary to study the networks considering time delay. In Ref. [25], Liu at al. study the pinning control problem of complex networks. But they only obtain asymptotically stable criteria.

In this paper, we will study the pinning control problem of complex dynamical networks with time delay. The objective is to stabilize the network onto some desired homogenous stationary states by injecting some

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controllers into a small fraction of network nodes. Several theorems and corollaries are established. Delay-dependent controlled asymptotically stability criteria and exponentially stability criteria in terms of Linear Matrix Inequality (LMI) for network are derived, which are proved by Lyapunov’s direct method.

2 Model Description and Preliminaries

Let’s consider a complex dynamical network consisting of \( N \) identical coupled nodes with time delay, with each node being an \( m \)-dimensional dynamical system:

\[
\dot{x}_i(t) = f(x_i(t)) + e \sum_{j=1}^{N} a_{ij} \Gamma x_j(t - \tau), \quad i = 1, 2, \ldots, N,
\]

where \( x_i = (x_{i1}, x_{i2}, \ldots, x_{im})^T \in \mathbb{R}^m \) are the state variables of node \( i \), \( f(\cdot) \) is a given nonlinear continuously differentiable function describing the dynamics of the complex network, the constant \( c > 0 \) represents the coupling strength, and the constant \( \tau > 0 \) is the time delay. \( \Gamma = (\gamma_{ij}) \in \mathbb{R}^{m \times m} \) is the inner-coupling matrix, and if some pairs \((i, j), 1 \leq i, j \leq m, \gamma_{ij} \neq 0\), then it means two coupled nodes are linked through their \( i \)th and \( j \)th state variable, respectively. Note here it is assumed that each pair of nodes has the same inner-coupling matrix for simplicity, though they are mostly different in actual networks.

In network (1), the coupling matrix \( A = (a_{ij}) \in \mathbb{R}^{N \times N} \) represents the outer-coupling configuration of the network, which is assumed as a random network described by the ER model or a scale-free network described by the BA (Barabási-Albert) model. If there is a connection between node \( i \) and node \( j \) (\( i \neq j \)), then \( a_{ij} = a_{ji} = 1 \); Otherwise, \( a_{ij} = a_{ji} = 0 \) (\( i \neq j \)), and \( \sum_{j=1, j \neq i}^{N} a_{ij} = \sum_{j=1, j \neq i}^{N} a_{ji} = k_i, a_{ii} = -k_i, i = 1, 2, \ldots, N \). Suppose there are no isolated nodes in the network, then \( A \) is an irreducible real symmetric matrix.

Before stating the main results of this paper, some definitions and preliminaries need to be given for convenient analysis.

Definition 1 System \( \dot{x}(t) = f(x(t)) \) is said to be exponentially stable with decay rate \( \alpha \) if system \( z(t) = e^{\alpha t}x(t) \) is asymptotically stable for some constant \( \alpha > 0 \).

Lemma 1 (Liu et al. [25]) Suppose \( A = (a_{ij})_{N \times N} \) is a real symmetric and irreducible matrix, in which \( a_{ij} \geq 0 \) (\( j \neq i \)) and \( a_{ii} = -\sum_{j=1, j \neq i}^{N} a_{ij} \), nonzero matrix \( D = \text{diag}(d_1, d_2, \ldots, d_N) \) satisfies \( d_i \geq 0 \) (\( 1 \leq i \leq N \)). Let \( B = A - D \), then

(i) all the eigenvalues of \( B \) are less than 0;
(ii) there exists an orthogonal matrix, \( \Phi = (\phi_1, \phi_2, \ldots, \phi_N) \in \mathbb{R}^{N \times N} \), such that

\[
B^T \phi_k = \lambda_k \phi_k, \quad (k = 1, 2, \ldots, N),
\]

where \( \lambda_1, \lambda_2, \ldots, \lambda_N \) are the eigenvalues of \( B \).

Lemma 2 (Moon et al. [26]) Assume that \( a, b \in \mathbb{R}^n \) are vectors, then for any positive-definite matrix \( X \in \mathbb{R}^{n \times n} \), the following inequality holds:

\[
-2a^T b \leq \inf_{X > 0} \{ a^T X a + b^T X^{-1} b \}.
\]

3 Control of dynamical networks with time delays

The object here is that we want to stabilize network (1) onto a homogeneous stationary state defined by

\[
x_1(t), x_2(t), \ldots, x_N(t) \to \bar{x}(t), \tag{2}
\]

where \( f(\bar{x}(t)) = 0 \), as \( t \to \infty \).

To achieve the goal (2), we apply the feedback control strategy on a small fraction \( \delta \) (\( 0 < \delta \leq 1 \)) of the nodes in network (1). Suppose that nodes \( i_1, i_2, \ldots, i_l \) are selected to be under control, where \( l = \lfloor \delta N \rfloor \)

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stands for the smaller but nearest integer to the real number $\delta N$. This controlled network can be described as

$$\dot{x}_i(t) = f(x_i(t)) + c \sum_{j=1}^{N} a_{ij} \Gamma x_j(t - \tau) + u_{ik}(t), \quad k = 1, 2, \ldots, l,$$

$$\dot{x}_i(t) = f(x_i(t)) + c \sum_{j=1}^{N} a_{ij} \Gamma x_j(t - \tau), \quad k = l + 1, l + 2, \ldots, N,$$

(3)

(4)

The local linear negative feedback control law we applied is as follows:

$$u_{ik}(t) = -cd_i \Gamma(x_i(t - \tau) - \bar{x}(t - \tau)), \quad i = 1, 2, \ldots, l,$$

(5)

where the feedback gain $d_i > 0$.

Combining (3), (4) and (5), and letting $d_j = 0$ if $j \in \{i_{i+1}, i_{i+2}, \ldots, i_N\}$, we have

$$\dot{x}_i(t) = f(x_i(t)) + c \sum_{j=1}^{N} a_{ij} \Gamma x_j(t - \tau) - cd_i \Gamma(x_i(t - \tau) - \bar{x}(t - \tau)), \quad i = 1, 2, \ldots, N.$$  

(6)

Let

$$e_i(t) = x_i(t) - \bar{x}(t), \quad i = 1, 2, \ldots, N.$$

(7)

Define the following matrix

$$D = diag(d_1, d_2, \ldots, d_N) \in \mathbb{R}^{N \times N}.$$  

(8)

Now linearizing the controlled network (6) on the homogenous stationary state $\bar{x}(t)$ leads to

$$\dot{e}(t) = e(t)J^T(t) + cB(e(t) - \bar{x}(t))\Gamma,$$

(9)

where $J(t) \in \mathbb{R}^{m \times m}$ is the Jacobian Matrix of $f$ on $\bar{x}(t)$,

$$e(t) = (e_1(t), e_2(t), \ldots, e_N(t))^T \in \mathbb{R}^{N \times m},$$

and $B = A - D$.

From Lemma 1, we know that the symmetric matrix $B$ is negative definite. Let $0 > \lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \cdots \geq \lambda_N$ be the eigenvalues of matrix $B$ and $\Phi = (\phi_1, \phi_2, \ldots, \phi_N) \in \mathbb{R}^{N \times N}$ be the corresponding (generalized) eigenvectors, which satisfy

$$B\phi_k = \lambda_k \phi_k, \quad k = 1, 2, \ldots, N.$$

(10)

By expanding each column of $e(t)$ on the basis $\Phi$, we obtain

$$e(t) = \Phi \eta(t).$$

(11)

Then (8) can be expanded into the following equations

$$\dot{\eta}(t) = \eta(t)J^T(t) + c\Lambda \eta(t - \tau)\Gamma,$$

(12)

where $\Lambda = diag(\lambda_1, \lambda_2, \ldots, \lambda_N)$.

Furthermore, we can obtain

$$\dot{\eta}_k(t) = J(t)\eta_k(t) + c\lambda_k \Gamma \eta_k(t - \tau), \quad k = 1, 2, \ldots, N,$$

(13)

where $\eta_k^T(t)$ is the $k$th row of $\eta(t)$.

Hence, the stability problem of the $(N \times m)$-dimensional system (6) is converted into the stability problem of the $N$ independent of $m$-dimensional linear system (12). In the following, $(A)^*$ means $A + A^T$ for a square matrix $A$. 

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Theorem 1 Consider the controlled network (12) with time-invariant delay $\tau > 0$, if for any $k$, $1 \leq k \leq N$, there exist two symmetric positive-definite matrices $P, Q \in \mathbb{R}^{m \times m}$, such that the following LMI holds,
\[
\begin{bmatrix}
[P(J(t) + c\lambda_k \Gamma)]^s + \tau Q & \tau c\lambda_k (J(t) + c\lambda_k \Gamma)^T P \\
\tau c\lambda_k \Gamma^T P(J(t) + c\lambda_k \Gamma) & -\tau Q
\end{bmatrix} < 0, \tag{13}
\]
then this network is asymptotically stable about (2).

Proof. Let $y(t) = \eta_k(t)$, and construct a Lyapunov function
\[
V(y(t)) = L^T(t) PL(t) + \int_{-\tau}^{0} \int_{t+s}^{t} y^T(\mu) Q y(\mu) ds ds,
\]
where $L(t) = y(t) + c\lambda_k \Gamma \int_{-\tau}^{t} y(s) ds$. Obviously, $V(y(t))$ is positive-definite.

The derivative of $V(y(t))$ along the trajectories of the controlled network (12) is
\[
\dot{V}(y(t)) = L^T(t) PL(t) + L^T(t) P \dot{L}(t) y(t) + \int_{t-\tau}^{t} y^T(s) Q y(s) ds = V_1 + V_2,
\]
where
\[
V_1 = y^T(t) \{[P(J(t) + c\lambda_k \Gamma)]^s + \tau Q \} y(t) - \int_{t-\tau}^{t} y^T(s) Q y(s) ds,
\]
\[
V_2 = 2c\lambda_k y^T(t) (J(t) + c\lambda_k \Gamma)^T P \Gamma \int_{t-\tau}^{t} y(s) ds.
\]

Let $a = c\lambda_k y^T(t)(J(t) + c\lambda_k \Gamma)^T P \Gamma$, $b = -y(s)$, $X = Q^{-1} > 0$ in Lemma 2, we have
\[
V_2 \leq \tau c^2 \lambda_k^2 y^T(t) (J(t) + c\lambda_k \Gamma)^T P \Gamma Q^{-1} \Gamma^T P(J(t) + c\lambda_k \Gamma)y(t) + \int_{t-\tau}^{t} y^T(s) Q y(s) ds.
\]

Then we obtain
\[
\dot{V}(y(t)) \leq y^T(t) Sy(t),
\]
where $S = [P(J(t) + c\lambda_k \Gamma)]^s + \tau Q + \tau c^2 \lambda_k^2 (J(t) + c\lambda_k \Gamma)^T P \Gamma Q^{-1} \Gamma^T P(J(t) + c\lambda_k \Gamma)$.

Using the Schur complements [28], we show that Eq.(13) guarantees $S < 0$. Thus we have $\dot{V}(y(t)) < 0$ for all $N$ equations in the linear system (12). From the Lyapunov stability theory, the controlled network (12) is asymptotically stable about (2) for delay time $\tau > 0$. This completes the proof of Theorem 1.

If the time-invariant delay $\tau \in (0, \bar{\tau}]$, we have
\[
S \leq [P(J(t) + c\lambda_k \Gamma)]^s + \tau Q + \tau c^2 \lambda_k^2 (J(t) + c\lambda_k \Gamma)^T P \Gamma Q^{-1} \Gamma^T P(J(t) + c\lambda_k \Gamma).
\]

Then based on Theorem 1, we can obtain the following corollary to find the boundary on the allowable delay time $\tau$ which maintains the delay-dependent stability of the complex dynamical networks with time-delay (12).

Corollary 1 The controlled network (12) is asymptotically stable about (2) for delay time $\tau \in (0, \bar{\tau})$, if for any $k$, $1 \leq k \leq N$, there exist two symmetric positive-definite matrices $P, Q \in \mathbb{R}^{m \times m}$, such that
\[
\begin{bmatrix}
[P(J(t) + c\lambda_k \Gamma)]^s + \tau Q & \tau c\lambda_k (J(t) + c\lambda_k \Gamma)^T P \\
\tau c\lambda_k \Gamma^T P(J(t) + c\lambda_k \Gamma) & -\tau Q
\end{bmatrix} < 0. \tag{14}
\]

Now consider the controlled time-delay systems (12) utilizing the following transformation:
\[
z_k(t) = e^{\alpha t} \eta_k(t), \quad k = 1, 2, \ldots, N, \tag{15}
\]
where $\alpha > 0$ is the delay decay rate, to transform (12) into
\[
\dot{z}_k(t) = [J(t) + \alpha I_m] z_k(t) + c\lambda_k e^{\alpha t} \Gamma z_k(t - \tau), \quad k = 1, 2, \ldots, N, \tag{16}
\]
where $I_m \in \mathbb{R}^{m \times m}$ is a unit matrix.

Then the controlled network (12) is exponential stable with decay rate $\alpha$ if the system (16) is asymptotically stable. By applying Theorem 1 to system (16), we can immediately get the following Theorem 2.
Theorem 2 The controlled network (12) is exponential stable about (2) with decay rate $\alpha > 0$ for delay time $\tau > 0$, if for any $k$, $1 \leq k \leq N$, there exists two symmetric positive-definite matrices $P, Q \in \mathbb{R}^{m \times m}$, such that

$$
\begin{bmatrix}
(PH(t))^s + \tau Q & \tau c \lambda_k e^{\alpha \tau} H^T(t) PT \\
\tau c \lambda_k e^{\alpha \tau} \Gamma^T PH(t) & -\tau Q
\end{bmatrix} < 0,
$$

(17)

where $H(t) = J(t) + \alpha I_m + c \lambda_k e^{\alpha \tau} \Gamma$.

Let $Q$ in (17) be the unit matrix $I_m$ for simplification, we can also get the following constructive corollary.

Corollary 2 The controlled network (12) is exponential stable about (2) with decay rate $\alpha > 0$ for delay time $\tau > 0$, if for any $k$, $1 \leq k \leq N$, there exists a symmetric positive-definite matrix $P \in \mathbb{R}^{m \times m}$, such that

$$
\begin{bmatrix}
(PH(t))^s + \tau I_m & \tau c \lambda_k e^{\alpha \tau} H^T(t) PT \\
\tau c \lambda_k e^{\alpha \tau} \Gamma^T PH(t) & -\tau I_m
\end{bmatrix} < 0,
$$

(18)

where $H(t) = J(t) + \alpha I_m + c \lambda_k e^{\alpha \tau} \Gamma$.

Remark 1 The principle of pinning control is to inject feedback control to a small fraction of nodes, owing to the coupling between the nodes of the network, in order to stabilize the whole network on the equilibrium point. According to Theorem 1 and Theorem 2, the stabilization of a network is determined to the Jacobian matrix $J(t)$, inner-coupling matrix $\Gamma$, coupling strength $c$, outer-coupling matrix $A$ and feedback gain matrix $D$. The efficiency of pinning control is great, since the number of controllers is very small compared to the scale of entire network. According to Lemma 1, B is symmetric and negative even if there is only one non-zero element in $D$. In a network of large scale, if we choose the right node to be pinned, appropriate $c$ and $D$, it is concluded that such a weighted complex dynamical network can be pinned to its equilibrium by using only one controller.

4 Simulation Study

The control theories analysis above can be applied to networks with different topologies and different size. For simplicity, we consider a four-node network, in which each node is a chaotic Rössler’s oscillator described in Ref. [29].

$$
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix} = \begin{bmatrix}
-(x_2 + x_3) \\
x_1 + p_1 x_2 \\
x_3 (x_1 - p_3) + p_2
\end{bmatrix}.
$$

(19)

Assume that the coupled configuration matrix is

$$
A = \begin{bmatrix}
-2 & 1 & 1 & 0 \\
1 & -3 & 1 & 1 \\
1 & 1 & -3 & 1 \\
0 & 1 & 1 & -2
\end{bmatrix}.
$$

The inner-coupling matrix $\Gamma = diag(1, 1, 1)$ and the feedback gains are set as the same value for the reason of simplicity, i.e. $d_{ki} = d$, for $k = 1, 2, ..., l$. Here we choose the second, the third and the fourth node to apply pinning control strategy.

If we take the system parameters $p_1 = p_2 = 0.2$ in (19) and choose $p_3$ as one of the following values: 2, 2.3, 3.5, 4.7, 5.0, 5.7, 6, 7, 8, 9, 10, 11, then every single node shows chaos state. Here we select 5.7, thus one of the unstable equilibrium point of the oscillator (19) is $\bar{x} = (5.6930, -28.4649, 28.4649)^T$.

Applying the condition (13) of Theorem 1, we let $Q = I_3$, choose the coupling strength $c = 0.2$ and the feedback gain $d = 2.4$. By using the Matlab LMI Toolbox, the network described above is asymptotically stable for the time delay $\tau < 0.0502$. Figure 1 shows the control results when $c = 0.2$, $d = 2.4$, $\tau = 0.03$. 

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Then we verify the condition (17) of Theorem 2, the second and the third node are selected to inject linear feedback control and the feedback gains are set as $c = 0.9$. When $\alpha$ is set as 0.2, $\tau$ is 0.08, we can obtain four pairs of two symmetric positive definite matrices $P_1$, $Q_1$:

$$P_1 = \begin{bmatrix} 18.7746 & -1.2744 & 1.8232 \\ -1.2744 & 13.9554 & -0.4815 \\ 1.8232 & -0.4815 & 1.7094 \end{bmatrix}, \quad Q_1 = \begin{bmatrix} 711.9258 & -15.6022 & -20.3255 \\ -15.6022 & 451.6192 & -4.9110 \\ -20.3255 & -4.9110 & 155.0929 \end{bmatrix},$$

$$P_2 = \begin{bmatrix} 34.1570 & -2.3792 & 3.4324 \\ -2.3792 & 23.3880 & -0.7604 \\ 3.4324 & -0.7604 & 2.7848 \end{bmatrix}, \quad Q_2 = \begin{bmatrix} 858.2035 & -18.6621 & -14.9830 \\ -18.6621 & 524.2466 & -0.8230 \\ -14.9830 & -0.8230 & 204.6290 \end{bmatrix},$$

$$P_3 = \begin{bmatrix} 2.4229 & -0.0543 & 0.0860 \\ -0.0543 & 1.2348 & 0.0298 \\ 0.0860 & 0.0298 & 0.0951 \end{bmatrix}, \quad Q_3 = \begin{bmatrix} 8.2929 & -0.1067 & -0.2024 \\ -0.1067 & 5.4113 & 0.2890 \\ -0.2024 & 0.2890 & 2.3738 \end{bmatrix},$$

$$P_4 = \begin{bmatrix} 124.8603 & -1.3932 & 2.3049 \\ -1.3932 & 67.2240 & 1.8439 \\ 2.3049 & 1.8439 & 4.4903 \end{bmatrix}, \quad Q_4 = \begin{bmatrix} 271.4101 & -2.0451 & -4.2642 \\ -2.0451 & 157.4835 & 9.8118 \\ -4.2642 & 9.8118 & 58.8963 \end{bmatrix}.$$

Suppose $\Lambda = (\lambda_1, \lambda_2, \lambda_3, \lambda_4)^T$ is the eigenvalues vector of $B$, the subscripts of $P$ and $Q$ correspond to the order of the eigenvalues. Figure 2 shows the control results when $c = 0.9$, $d = 4$, $\tau = 0.08$.

With the parameters unchanged, we find that only if $\tau \leq 0.1082$, we can obtain two symmetric positive definite matrices $P$, $Q$. So we obtain the boundary of time delay under such parameters.

By changing the value of decay rate $\alpha$, with the other parameters being fixed, we obtain the boundary of the delay time as shown in Table 1. According to the simulation result, we notice that the boundary of time

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**Figure 1:** Control results: (a)$x_{i1}$; (b)$x_{i2}$; (c)$x_{i3}$, $i = 1, 2, 3, 4$
Figure 2: Control results, (a) $x_{i1}$; (b) $x_{i2}$; (c) $x_{i3}$, $i = 1, 2, 3, 4$

delay is monotonically decreasing with respect to the decay rate $\alpha$. The reason is that bigger $\alpha$ means faster convergence of the system, which requires smaller delay correspondingly.

Table 1: $\alpha$ vs. boundary of time delay

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>Boundary of time delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1095</td>
</tr>
<tr>
<td>0.2</td>
<td>0.1082</td>
</tr>
<tr>
<td>0.3</td>
<td>0.1070</td>
</tr>
<tr>
<td>0.4</td>
<td>0.1061</td>
</tr>
<tr>
<td>0.5</td>
<td>0.1005</td>
</tr>
<tr>
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<td>0.0841</td>
</tr>
<tr>
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<tr>
<td>0.8</td>
<td>0.0498</td>
</tr>
<tr>
<td>0.9</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

We can also select one of the four nodes to inject controller in the above simulations according to the Remark in section 2. The main difference of such case is that it may be harder to find suitable matrices satisfying Theorem 1 or Theorem 2 in some parameter setting conditions.

5 Conclusions

Time delays commonly exist in the real world and the strength of the connections may also affect the controlling result. So in this paper, general weighted complex dynamical networks with time delays, which are
connected and undirected, are considered. In this paper, our aim is to investigate exponential stability for general complex dynamical networks by applying local linear feedback controllers to a small fraction of network nodes. The placement of the controllers is determined by the topology of the network. Generally, we select most highly connected nodes to be pinned in scale-free networks. Several theorems are derived in this paper and numerical examples are given to illustrate both asymptotical and exponential ability conditions.

This paper only considers networks with the same time delay, and there is more work for us to deal with the case of multiple time delay. Deriving delay-dependent condition for exponential stability case is also our future work.

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