Research Article

A Decentralized Routing Control Scheme for Data Communication Networks

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Received 11 January 2013; Accepted 4 March 2013

Academic Editor: Engang Tian

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This paper studies the decentralized routing control of data communication networks. Taking the physical constraints on the data flow and the network-induced delays into consideration, the decentralized routing control problem is reformulated as a constrained control problem, and the restriction of initial message lengths is no longer needed. By defining a general Lyapunov functional and applying a reciprocally convex combination technique to deal with the network-induced delays, less conservative and less complex designing conditions are obtained in terms of linear matrix inequalities (LMIs). A simulation example is also given to illustrate the effectiveness of the proposed designing scheme.

1. Introduction

Routing control plays an indispensable role in complex and crowded networks such as transportation networks and data communication networks [1–19]. The fundamental idea of routing control is that the most suitable route for data packets from source to destination through other nodes is to be determined such that certain objective functions are minimized.

Early routing algorithms, such as those implemented in the ARPANET [2] and TYMNET [3], were designed for optimally achieving some prespecified objective, such as *shortest time* or *shortest path* from the initial node to the destination node, *minimization of a cost function* related to the link congestion [14], or *minimization of a generic measure* of link flows. However, the performance of the crowded networks with these routing algorithms will deteriorate significantly, since the channel communication capacity is usually limited and the link congestion problems may often occur in many practical networks [20]. Therefore, it is essential to take the physical constraints, such as limited channel capacity and limited energy source, into consideration in designing proper routing control scheme.

It is very known that the network-induced delays (i.e., transmission delay, propagation delay, and processing delay) may induce instability, oscillation, and poor performance, and have a major impact on the routing control design. Several researchers have also attempted to address the problem of delay-constrained routing in recent years [13–19, 21–24]. Different techniques such as capacity allocation [16] and neural networks [19] are adopted to obtain the proper routing paths that minimizing or guaranteeing the boundedness of different types of network delays. However, more general index may be specified in evaluating the network performance, and many physical constraints of networks also should be taken into consideration. Under such a circumstances, the routing control problem becomes a difficult task and cannot be tackled with the above-mentioned methods. As stated in [18, 19], the fluid flow conservation principle is frequently employed in deriving the queuing dynamics, wherein each state of the subsystem (node) represents a queue corresponding to a given destination node. With the aid of linear matrix inequality (LMI) approach, the recent paper [20] provides a promising framework to revisit and reformulate the routing control problems as a constrained H_∞ optimal control problem for time-delay systems; hence, a number of

physical constraints can be easily imposed on the routing problem.

In [20], a continuous-time system model was used to describe the dynamics of traffic networks, and the physical constraints on traffic flows and queues were transformed into a set of LMI-based conditions. Then, robust centralized as well as decentralized routing control strategies were introduced for networks with a fixed topology based on the minimisation of the worst-case queuing length, which is related to the queuing delays. Similar treatment was adopted in [25]. It is worth pointing out that the derivatives of network-induced delays were assumed to be less than 1. However, according to [26], such assumptions are false. Meanwhile, a parameter should be given a priority and the initial values of all message queue lengths are required to be 0 in the transformation of the physical constraints, which may be harsh for many practical applications and may result in some conservatism.

In this paper, we study routing control of data communication networks that arise from many practical applications [19]. A discrete-time model instead of continuous-time model [20] is used to describe the communication network dynamics and the data constraints on the data flow. Furthermore, in order to facilitate the practical implementation for large-scale data communication networks, we are dedicated to design decentralized controllers instead of centralized controllers. Thus, vulnerable failures and large communication overheads in the network may be avoided. To this end, some new techniques will be adopted to tackle the extra difficulty in the related LMI manipulation and derivation, which are caused because of the decentralized controller structure. Different from the existing works, a reciprocally convex combination method is used to deal with delays, the physical constraints are successfully transformed into a set of LMIs and the restriction that initial message queue lengths should be 0 is removed, and each LMI-based condition involved in the designing of decentralized routing control is only related to an oriented link in the data communication network, which can effectively reduce both the conservatism and the complexity.

Notation. Throughout this paper, a real symmetric matrix $P > 0$ (≥ 0) denotes P being a positive definite (positive semidefinite) matrix, and $A > B$ ($A \geq B$) means $A - B > 0$ (≥ 0). I is used to denote an identity matrix with proper dimension. Matrices, if not explicitly stated, are assumed to have compatible dimensions. The symmetric terms in a symmetric matrix are denoted by $*$. For a real vector $x \in R^n$, $x \geq 0$ (> 0) denotes every component of x being nonnegative (positive). In this case, x is called nonnegative (positive). Likewise, $A \in R^{n \times m}$ is nonnegative or positive if every entry of A is nonnegative or positive, respectively, which is written as $A \geq 0$ or $A > 0$, respectively.

2. Problem Formulation

Consider a data communication network, $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, consisting of a directed graph with a set $\mathcal{N}$ of N nodes and a set $\mathcal{L}$ of L -oriented links. Each message has a destination

node $d \in \mathcal{N}$, and all destination nodes form a set $\mathcal{N}_d$. Each node $i \in \mathcal{N}$ receives messages from the upstream nodes within the network. Messages are absorbed as soon as they arrive at their destination nodes. Messages arriving to a node other than their final destination are put into a queue (or buffer) and eventually are sent out to a downstream node. It is assumed that the network is “connected,” that is, each node of the network must be reachable from each other node. In the worst case, where all the nodes are source as well as destination, at each node $i \in \mathcal{N}$ there will be $n - 1$ queues in which messages are stored for all destinations, $1, 2, \dots, i - 1, i + 1, \dots, N$. We also assume that the rate of messages that are sent from one node to another is updated (synchronously throughout the communication network) by control variables at discrete instants kT ($k = 0, 1, 2, \dots$), where T is a positive scalar.

Similar to [19], the data communication network dynamics can be expressed as

$$q_i^d(k+1) = q_i^d(k) + \sum_{\substack{j \in \mathcal{P}(i) \\ j \neq d}} f_{ji}^d(k - \tau_{ji}(k)) - \sum_{j \in \mathcal{S}(i)} f_{ij}^d(k),$$

$$i \in \mathcal{N}, d \in \mathcal{N}_d^i, \quad (1)$$

where $q_i^d(k)$: message queue length at node i destined to node d at instant kT ; $\mathcal{P}(i)$: set of upstream neighbors of node i ; $\mathcal{S}(i)$: set of downstream neighbors of node i ; $f_{ij}^d(k)$: traffic flow routed from node i to node j destined to node d at instant kT ; $\mathcal{N}_d^i$: subset of $\mathcal{N}_d$, that is, $\mathcal{N}_d^i = \mathcal{N}_d \setminus \{i\}$; $\tau_{ij}(k)$: time-varying delay in transmitting, propagating, and processing of messages (including identifying the destination, inserting in the queue, and routing computation) with destination d routed from node i to node j , which satisfies

$$0 \leq \tau_{ij}(k) \leq \tau_{ij}, \quad \forall (i, j) \in \mathcal{L}, \quad (2)$$

where τ_{ij} are constants.

Due to the physical significance of f_{ij}^d and the constraints on the data flow through each link and the message queue buffer size at each node, the following conditions should be satisfied:

$$f_{ij}^d(k) \geq 0, \quad i \in \mathcal{N}, j \in \mathcal{S}(i), d \in \mathcal{N}_d^i, \quad (3)$$

$$0 \leq \sum_{d \in \mathcal{N}_d^i} q_i^d(k) \leq q_i, \quad i \in \mathcal{N}, \quad (4)$$

$$\sum_{d \in \mathcal{N}_d^i} f_{ij}^d(k) \leq c_{ij}, \quad i \in \mathcal{N}, j \in \mathcal{S}(i), \quad (5)$$

where positive scalars q_i and c_{ij} represent the maximal length of the message queue length at node i and the maximal capacity of oriented link (i, j) (it is also called “edge”), respectively.

Define

$$x_i(k) = \text{vec} \{q_i^d(k)\}, \quad u_i(k) = \text{vec} \{f_{ij}^d(k)\},$$

$$(i \in \mathcal{N}, j \in \mathcal{S}(i), d \in \mathcal{N}_d^i), \quad (6)$$

then (1) can be rewritten as

$$x_i(k+1) = x_i(k) + B_i u_i(k) + \sum_{j \in \mathcal{P}(i)} B_{dji} u_j(k - \tau_{ji}(k)), \quad (7)$$

where $x_i(k) \in \mathbb{R}^{N_d^i}$ and $u_i(k) \in \mathbb{R}^{m_i N_d^i}$ are vectors; m_i , N_d , and N_d^i represent the numbers of nodes contained in $\mathcal{S}(i)$, $\mathcal{N}_d$, and $\mathcal{N}_d^i$, respectively; B_i and B_{dji} are constant matrices. Obviously, the entries of B_i are equal to 0 or -1 , and the ones of B_{dji} are equal to 0 or 1, which reflect the network connectivity of node i in graph $\mathcal{G}$ [20].

In this paper, a decentralized routing control scheme

$$u_i(k) = K_i x_i(k), \quad i \in \mathcal{N}, \quad (8)$$

is proposed to stabilize the origin system (1), where state feedback controllers K_i ($i \in \mathcal{N}$) are to be designed. Such a constrained control problem can be found by solving a set of linear matrix inequalities (LMIs). Different from the one given in [20], the obtained routing control scheme is at edge-level; that is, each inequality is only dependent on an edge (i, j) in $\mathcal{L}$. This implies that the dimension of each inequality is low, so the computational complexity is reduced effectively. In addition, since some constraints are discarded, the conservatism of the obtained LMI-based conditions is also reduced.

Through this paper, Jensen's integral inequality [27] and a reciprocally convex combination technique [28] will be used, so it is listed as the following lemmas.

Lemma 1 (see [27]). *For any positive symmetric constant matrix $M \in \mathbb{R}^{n \times n}$, scalars r_1, r_2 satisfying $r_1 < r_2$, a vector function $\omega : [r_1, r_2] \rightarrow \mathbb{R}^n$ such that the integrations concerned are well defined, then*

$$\begin{aligned} & \left(\int_{r_1}^{r_2} \omega(s) ds \right)^T M \left(\int_{r_1}^{r_2} \omega(s) ds \right) \\ & \leq (r_2 - r_1) \int_{r_1}^{r_2} \omega^T(s) M \omega(s) ds. \end{aligned} \quad (9)$$

Lemma 2 (see [29]). *For given positive semidefinite matrices Z_1 and Z_2 , if there exists a matrix T such that*

$$\begin{bmatrix} Z_1 & T \\ * & Z_2 \end{bmatrix} \geq 0, \quad (10)$$

then the following inequality for any α ($0 < \alpha < 1$) holds

$$\begin{bmatrix} \frac{1}{\alpha} Z_1 & 0 \\ * & \frac{1}{1-\alpha} Z_2 \end{bmatrix} \geq \begin{bmatrix} Z_1 & T \\ * & Z_2 \end{bmatrix}. \quad (11)$$

3. Main Results

3.1. Stability Analysis. Now, we give a new stability criterion for the origin of system (7) with (2) as follows.

Theorem 3. *For given scalars $\tau_{ij} > 0$ and K_i ($i \in \mathcal{N}$, $j \in \mathcal{S}(i)$), the origin of system (7) with (2) is globally asymptotically stable if there exist matrices $P_{ij} = P_{ij}^T > 0$, $Q_{ij} = Q_{ij}^T \geq 0$, $R_{ij} = R_{ij}^T \geq 0$, $Z_{ij} = Z_{ij}^T > 0$, and $U_{ij} = U_{ij}^T > 0$ ($\forall i \in \mathcal{N}$, $j \in \mathcal{S}(i)$) with appropriate dimensions, such that*

$$\begin{bmatrix} Z_{ij} & T_{ij} \\ * & Z_{ij} \end{bmatrix} \geq 0, \quad (12)$$

$$\begin{bmatrix} \Phi_{ij} & \Theta_{ij} \\ * & -U_{ij} \end{bmatrix} < 0, \quad (13)$$

where $i = 1, 2, \dots, n$ and $j \in \mathcal{S}(i)$, and

$$\begin{aligned} \Phi_{ij} &= \begin{bmatrix} \Phi_{ij}^{11} & \frac{1}{\tau_{ij}}(Z_{ij} - T_{ij}) & \frac{1}{\tau_{ij}}T_{ij} & \Phi_{ij}^{14} \\ * & \Phi_{ij}^{22} & \frac{1}{\tau_{ij}}(Z_{ij} - T_{ij}) & 0 \\ * & * & -R_{ij} - \frac{1}{\tau_{ij}}Z_{ij} & 0 \\ * & * & * & \Phi_{ij}^{44} \end{bmatrix}, \\ \Phi_{ij}^{11} &= \tau_{ij}Q_{ij} + R_{ij} - \frac{1}{\tau_{ij}}Z_{ij} \\ &\quad - \frac{1}{m_i} \left(M_{i1} B_i K_i + K_i^T B_i^T M_{i1}^T - M_{i1} \left(\sum_{l \in \mathcal{P}(i)} U_{li} \right) M_{i1}^T \right), \\ \Phi_{ij}^{14} &= P_{ij} \\ &\quad + \frac{1}{m_i} \left(M_{i1} - K_i^T B_i^T M_{i2}^T + M_{i1} \left(\sum_{l \in \mathcal{P}(i)} U_{li} \right) M_{i2}^T \right), \\ \Phi_{ij}^{22} &= -Q_{ij} - \frac{1}{\tau_{ij}}(2Z_{ij} - T_{ij} - T_{ij}^T), \\ \Phi_{ij}^{44} &= P_{ij} + \tau_{ij}Z_{ij} \\ &\quad + \frac{1}{m_i} \left(M_{i2} + M_{i2}^T + M_{i2} \left(\sum_{l \in \mathcal{P}(i)} U_{li} \right) M_{i2}^T \right), \\ \Theta_{ij} &= [0 \quad B_{dij} K_i \quad 0 \quad 0]^T. \end{aligned} \quad (14)$$

Proof. The proof is provided in the Appendix. $\square$

Remark 4. In Theorem 3, a sufficient condition of globally asymptotical stability for the origin of system (7) with (2) is given in terms of LMIs. Different from the one in [20], positive definite matrices P_{ij} , Q_{ij} , R_{ij} , and Z_{ij} correspond to the oriented link (i, j) , so the Lyapunov functional (A.1) is more general. Meanwhile, each inequality in (13) is also related to an oriented link (i, j) in $\mathcal{L}$, so its dimension is lower. Combined with using a reciprocally convex technique [28], the computational complexity and the conservatism are reduced.

3.2. A Decentralized Routing Control Scheme

3.2.1. Controller Design without the Physical Constraints.

From (13), one can find that $M_{i2} + M_{i2}^T$ ($i = 1, 2, \dots, n$) are negative definite, this implies that M_{i2} are nonsingular. Set

$$\begin{aligned} M_{i1} &= \varepsilon_i M_{i2}, & \overline{M}_{i2} &= M_{i2}^{-1}, & \overline{P}_{ij} &= \overline{M}_{i2} P_{ij} \overline{M}_{i2}^T, \\ \overline{Q}_{ij} &= \overline{M}_{i2} Q_{ij} \overline{M}_{i2}^T, & \overline{R}_{ij} &= \overline{M}_{i2} R_{ij} \overline{M}_{i2}^T, \\ \overline{Z}_{ij} &= \overline{M}_{i2} Z_{ij} \overline{M}_{i2}^T, & \overline{T}_{ij} &= \overline{M}_{i2} T_{ij} \overline{M}_{i2}^T, & F_i &= K_i \overline{M}_{i2}^T, \end{aligned} \quad (15)$$

pre- and postmultiplying the left side of inequality (13) by $\text{diag}\{\overline{M}_{i2}, \overline{M}_{i2}, \overline{M}_{i2}, \overline{M}_{i2}, I\}$ and its transpose, and from the Schur complement, we get the following.

Theorem 5. For given scalars $\tau_{ij} > 0$ and ε_i ($i \in \mathcal{N}$, $j \in \mathcal{S}(i)$), the origin of system (7) with (2) is globally asymptotically stable if there exist matrices $\overline{P}_{ij} = \overline{P}_{ij}^T > 0$, $\overline{Q}_{ij} = \overline{Q}_{ij}^T \geq 0$, $\overline{R}_{ij} = \overline{R}_{ij}^T \geq 0$, and $\overline{Z}_{ij} = \overline{Z}_{ij}^T > 0$, F_i and $\overline{M}_{i2}$ (for all $i \in \mathcal{N}$, $j \in \mathcal{S}(i)$) with appropriate dimensions, such that

$$\begin{bmatrix} \overline{Z}_{ij} & \overline{T}_{ij} \\ * & \overline{Z}_{ij} \end{bmatrix} \geq 0, \quad (16)$$

$$\begin{bmatrix} \Omega_{ij} & \Gamma_{ij} \\ * & -U_{ij} \end{bmatrix} < 0, \quad (17)$$

where $i \in \mathcal{N}$ and $j \in \mathcal{S}(i)$, and

$$\begin{aligned} \Omega_{ij} &= \begin{bmatrix} \Omega_{ij}^{11} & \frac{1}{\tau_{ij}} (\overline{Z}_{ij} - \overline{T}_{ij}) & \frac{1}{\tau_{ij}} \overline{T}_{ij} & \Omega_{ij}^{14} \\ * & \Omega_{ij}^{22} & \frac{1}{\tau_{ij}} (\overline{Z}_{ij} - \overline{T}_{ij}) & 0 \\ * & * & -\overline{R}_{ij} - \frac{1}{\tau_{ij}} \overline{Z}_{ij} & 0 \\ * & * & * & \Omega_{ij}^{44} \end{bmatrix}, \\ \Gamma_{ij} &= [0 \quad B_{dij} F_i \quad 0 \quad 0]^T, \\ \Omega_{ij}^{11} &= \tau_{ij} \overline{Q}_{ij} + \overline{R}_{ij} - \frac{1}{\tau_{ij}} \overline{Z}_{ij} \\ &\quad - \frac{1}{m_i} \varepsilon_i \left(B_i F_i + F_i^T B_i^T - \varepsilon_i \sum_{l \in \mathcal{P}(i)} U_{li} \right), \\ \Omega_{ij}^{14} &= \overline{P}_{ij} + \frac{1}{m_i} \left(\overline{M}_{i2}^T - F_i^T B_i^T + \sum_{l \in \mathcal{P}(i)} U_{li} \right), \\ \Omega_{ij}^{22} &= -\overline{Q}_{ij} - \frac{1}{\tau_{ij}} (2\overline{Z}_{ij} - \overline{T}_{ij} - \overline{T}_{ij}^T), \\ \Omega_{ij}^{44} &= \overline{P}_{ij} + \tau_{ij} \overline{Z}_{ij} + \frac{1}{m_i} \left(\overline{M}_{i2}^T + \overline{M}_{i2} + \sum_{l \in \mathcal{P}(i)} U_{li} \right). \end{aligned} \quad (18)$$

The gains K_i ($i \in \mathcal{N}$) of the subsystem controllers in (8) are given by

$$K_i = F_i \overline{M}_{i2}^{-T}. \quad (19)$$

3.2.2. LMI-Based Conditions for the Physical Constraints. Now, we translate the physical constraints (3)–(5) into LMI-based conditions.

(1) *Nonnegativity Constraint on Data Traffic Flow.* From (1), it is easy to see that the nonnegativity of $x_i(k)$ and $f_{ij}^d(k)$ can be guaranteed if $I + B_i K_i$ and K_i are nonnegative for all $i \in \mathcal{N}$, $j \in \mathcal{S}(i)$, and $d \in \mathcal{N}_d^i$.

Note that the negative definiteness of $\overline{M}_{i2} + \overline{M}_{i2}^T$, and from (17), the nonnegativity of $I + B_i K_i$ and K_i can be guaranteed if $\overline{M}_{i2}$ are diagonal for all $i \in \mathcal{N}$ and

$$\begin{aligned} \overline{M}_{i2} + B_i F_i &\leq 0, \\ F_i &\leq 0. \end{aligned} \quad (20)$$

(2) *Upper Bound on the Buffer Size.* Note that

$$\sum_{d \in \mathcal{N}_d^i} q_i^d(k) = H_i x_i(k), \quad (21)$$

where

$$H_i = \begin{bmatrix} 1 & \cdots & 1 \\ \hline & N_d^i & \end{bmatrix}. \quad (22)$$

So, the constraint (4) can be represented as

$$0 \leq H_i x_i(k) \leq q_i. \quad (23)$$

From $\Omega_{ij} < 0$, it follows that $\Omega_{ij}^{44} < 0$. So, there exist a small enough $\lambda > 0$ such that

$$\overline{P}_{ij} + \frac{1}{m_i} (\overline{M}_{i2}^T + \overline{M}_{i2} + \lambda I) < 0. \quad (24)$$

Since

$$-\frac{1}{\lambda} \overline{M}_{i2} \overline{M}_{i2}^T \leq \overline{M}_{i2}^T + \overline{M}_{i2} + \lambda I, \quad (25)$$

and $\overline{P}_{ij} = \overline{M}_{i2} P_{ij} \overline{M}_{i2}^T$, inequality (24) implies

$$\sum_{j \in \mathcal{S}(i)} P_{ij} < \frac{1}{\lambda} I. \quad (26)$$

If (16) and (17) in Theorem 5 are feasible, under the assumption $x_i(\tau) = 0$ for all $\tau \in \{-1, -2, \dots, -\tau_{ij}\}$, from

$$\begin{aligned} x_i^T(k) &\left(\sum_{j \in \mathcal{S}(i)} P_{ij} \right) x_i(k) \\ &\leq \sum_{i=1}^N x_i^T(k) \left(\sum_{j \in \mathcal{S}(i)} P_{ij} \right) x_i(k) \leq V(k), \end{aligned}$$

$$\begin{aligned}
V(0) &\leq \frac{1}{\lambda} \sum_{i=1}^N x_i^T(0) x_i(0) \\
&\leq \frac{1}{\lambda} \sum_{i=1}^N x_i^T(0) H_i^T H_i x_i(0) \leq \frac{1}{\lambda} \sum_{i=1}^N q_i^2,
\end{aligned} \tag{27}$$

we get

$$x_i^T(k) \left(\sum_{j \in \mathcal{S}(i)} P_{ij} \right) x_i(k) \leq \frac{1}{\lambda} \sum_{i=1}^N q_i^2, \tag{28}$$

where $V(k)$ is defined in (A.1).

Thus, (23) can be guaranteed if

$$\frac{1}{m_i q_i^2} H_i^T H_i \leq \frac{\lambda}{\sum_{i=1}^N q_i^2} P_{ij}, \quad \forall j \in \mathcal{S}(i). \tag{29}$$

From the Schur complement, the above inequality is equivalent to

$$\begin{bmatrix} -\bar{P}_{ij} & \bar{M}_{i2} H_i^T \\ * & -\frac{m_i q_i^2}{\sum_{i=1}^N q_i^2} \lambda \end{bmatrix} < 0. \tag{30}$$

So, from the above analysis, it is known that (23) can be guaranteed if (24) and (30) hold for any $(i, j) \in \mathcal{L}$.

(3) *Capacity Constraints on Links.* For $j \in \mathcal{S}(i)$, it is known that there exists a nonnegative integer i_j such that the numbers of i_j nodes contained in $\mathcal{S}(i)$ are less than j and the ones of $m_i - i_j - 1$ nodes contained in $\mathcal{S}(i)$ are greater than j . Thus, We get

$$\sum_{d \in \mathcal{N}_d^i} f_{ij}^d(k) = G_{ij} u_i(k), \quad \forall (i, j) \in \mathcal{L}, \tag{31}$$

where

$$G_{ij} = \begin{bmatrix} \underbrace{0 \cdots 0}_{i_j \times N_d^i} & \underbrace{1 \cdots 1}_{N_d^i} & \underbrace{0 \cdots 0}_{(m_i - i_j - 1) \times N_d^i} \end{bmatrix}. \tag{32}$$

so the constraint (5) can be represented as

$$0 \leq G_{ij} u_i(k) \leq c_{ij}. \tag{33}$$

Similarly, constraint (33) can be satisfied if (24) and

$$\begin{bmatrix} -\bar{P}_{ij} & F_i^T G_{ij}^T \\ * & -\frac{c_{ij}^2}{\sum_{i=1}^N q_i^2} \lambda \end{bmatrix} < 0. \tag{34}$$

Therefore, considering the physical constraints (3)–(5), a decentralized routing control scheme can be get as follows.

Theorem 6. For given scalars $\tau_{ij} > 0$ and ε_i ($i \in \mathcal{N}$, $j \in \mathcal{S}(i)$), the origin of system (7) with (2) is globally asymptotically stable

FIGURE 1: Topology of a communication network.

FIGURE 2: State response of $x_1(k)$.

if there exist a scalar $\lambda > 0$, matrices $\bar{P}_{ij} = \bar{P}_{ij}^T > 0$, $\bar{Q}_{ij} = \bar{Q}_{ij}^T \geq 0$, $\bar{R}_{ij} = \bar{R}_{ij}^T \geq 0$, and $\bar{Z}_{ij} = \bar{Z}_{ij}^T > 0$, F_i and diagonal matrices $\bar{M}_{i2}$ (for all $i \in \mathcal{N}$, $j \in \mathcal{S}(i)$) with appropriate dimensions, such that (16), (17), (20), (24), (30), and (34) hold.

Correspondingly, the gains K_i of the subsystem controllers in (8) are given by (19).

Remark 7. In [20, 25], a scalar λ was needed to be selected before and the restriction $V(0) = 0$ in transforming the physical constraints into LMI-based conditions. Contrastively, λ involved in inequalities (30) and (34) is a variable and it can be found by solving these LMIs. More importantly, the restriction $V(0) = 0$ is not needed here.

Remark 8. Different from [20, 25], positive definite matrix $\bar{P}$ in Theorem 6 is not required to be diagonal, which discards the constraint on P .

4. Numerical Example

Consider a data communication network shown in Figure 1 [20, 30]. The capacity of each link is also indicated in

the figure, the unit of which is kbit/sec. All the nodes are assumed to be sources as well as destinations. From Figure 1, it follows that there are 6 queues (the states of the system) and 8 output flows for these queues (the input signals). The queue dynamic of the communication network can be described as follows

$$\begin{aligned} x_1(k+1) &= x_1(k) + B_1 u_1(k) + B_{d31} u_3(k - \tau_{31}(k)), \\ x_2(k+1) &= x_2(k) + B_2 u_2(k) + B_{d12} u_1(k - \tau_{12}(k)) \\ &\quad + B_{d32} u_3(k - \tau_{32}(k)), \\ x_3(k+1) &= x_3(k) + B_3 u_3(k) + B_{d23} u_2(k - \tau_{23}(k)), \end{aligned} \quad (35)$$

where

$$\begin{aligned} x_1(k) &= \begin{bmatrix} q_1^2(k) \\ q_1^3(k) \end{bmatrix}, & x_2(k) &= \begin{bmatrix} q_2^1(k) \\ q_2^3(k) \end{bmatrix}, \\ x_3(k) &= \begin{bmatrix} q_3^1(k) \\ q_3^2(k) \end{bmatrix}, & u_1(k) &= \begin{bmatrix} f_{12}^2(k) \\ f_{12}^3(k) \end{bmatrix}, \\ u_2(k) &= \begin{bmatrix} f_{23}^1(k) \\ f_{23}^3(k) \end{bmatrix}, & u_3(k) &= \begin{bmatrix} f_{31}^1(k) \\ f_{31}^2(k) \\ f_{32}^1(k) \\ f_{32}^2(k) \end{bmatrix}, \\ B_1 = B_2 &= \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}, & B_{d31} &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \\ B_{d12} &= \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}, & B_{d32} &= \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \\ B_3 &= \begin{bmatrix} -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & -1 \end{bmatrix}, & B_{d23} &= \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}. \end{aligned} \quad (36)$$

Assume that the maximal buffer sizes, q_i ($i \in \mathcal{N}$), are given by $q_1 = 10$, $q_2 = 15$, and $q_3 = 20$. For the case of $\tau_{ij} = 5$ for all $(i, j) \in \mathcal{L}$, by Theorem 6 with $\varepsilon_i = 4$, one can get

$$\begin{aligned} K_1 &= \begin{bmatrix} 0.2035 & 0.0001 \\ 0.0001 & 0.1971 \end{bmatrix}, & K_2 &= \begin{bmatrix} 0.1934 & 0 \\ 0 & 0.2037 \end{bmatrix}, \\ K_3 &= \begin{bmatrix} 0.2219 & 0 \\ 0 & 0.1743 \\ 0.1388 & 0 \\ 0 & 0.1736 \end{bmatrix}. \end{aligned} \quad (37)$$

Now, we provide a simulation.

Suppose that the initial states of $x_i(k)$ are given by $x_1(0) = [6, 3]^T$, $x_2(0) = [5, 8]^T$ and $x_3(0) = [9, 9]^T$. With the obtained controller gains in (37), the state responses of the system are depicted in Figures 2, 3, and 4, which shows that the system is asymptotically stable. Figures 5, 6, 7, and 8 show

FIGURE 3: State response of $x_2(k)$.

FIGURE 4: State response of $x_3(k)$.

the data flows between nodes in the communication network. From Figures 5–8, one can see that the physical constraints are satisfied although initial state $x(0)$ is not equal to 0. So, the proposed decentralized routing control scheme is effective.

5. Conclusion

In this paper, the routing control problem of data communication networks has been investigated. By considering both the network-induced delays and the physical constraints, a decentralized routing control scheme is proposed, which can be realized by solving a set of LMIs. Since a method is used to relax the transformation conditions of the physical constraints, and a reciprocally convex combination technique is

FIGURE 5: Data flow from node 1 to node 2.

FIGURE 7: Data flow from node 3 to node 1.

FIGURE 6: Data flow from node 2 to node 3.

FIGURE 8: Data flow from node 3 to node 2.

employed to dealing with the network-induced delays, a less complex and less conservative designing result is obtained. A simulation example is given to illustrate the effectiveness of the presented designing scheme.

Appendix

Proof of Theorem 3. Choose a Lyapunov functional as

$$V(k) = V_1(k) + V_2(k) + V_3(k) + V_4(k), \quad (\text{A.1})$$

where

$$V_1(k) = \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} x_j^T(k) P_{ji} x_j(k),$$

$$V_2(k) = \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \left(\sum_{l=k-\tau_{ji}(k)}^{k-1} x_j^T(l) Q_{ji} x_j(l) + \sum_{l=-\tau_{ji}+1}^0 \sum_{r=k+l}^{k-1} x_j^T(r) Q_{ji} x_j(r) \right),$$

$$\begin{aligned}
V_3(k) &= \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \sum_{l=k-\tau_{ji}}^{k-1} x_j^T(l) R_{ji} x_j(l), \\
V_4(k) &= \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \sum_{l=-\tau_{ji}}^{-1} \sum_{r=k+l}^{k-1} \eta_j^T(r) Z_{ji} \eta_j(r),
\end{aligned} \tag{A.2}$$

and $P_{ij} = P_{ij}^T > 0$, $Q_{ij} = Q_{ij}^T \geq 0$, $R_{ij} = R_{ij}^T \geq 0$, $Z_{ij} = Z_{ij}^T > 0$ (for all $i \in \mathcal{N}$, $j \in \mathcal{S}(i)$) are to be determined.

Note that

$$\sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} x_j^T(k) P_{ji} x_j(k) = \sum_{i=1}^n \sum_{j \in \mathcal{S}(i)} x_i^T(k) P_{ij} x_i(k), \tag{A.3}$$

We get

$$\begin{aligned}
\Delta V_1(k) &= \sum_{i=1}^n \sum_{j \in \mathcal{S}(i)} \left(x_i^T(k+1) P_{ij} x_i(k+1) - x_i^T(k) P_{ij} x_i(k) \right) \\
&= \sum_{i=1}^n \sum_{j \in \mathcal{S}(i)} \left(\eta_i^T(k) P_{ij} \eta_i(k) + \eta_i^T(k) P_{ij} x_i(k) \right. \\
&\quad \left. + x_i^T(k) P_{ij} \eta_i(k) \right).
\end{aligned} \tag{A.4}$$

Similarly, taking the differences of $V_i(k)$ ($i = 2, 3, 4$) along the trajectory of (7) yields that

$$\begin{aligned}
\Delta V_2(k) &= \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \left\{ \left(\sum_{l=k+1-\tau_{ji}(k+1)}^k x_j^T(l) Q_{ji} x_j(l) \right. \right. \\
&\quad \left. \left. - \sum_{l=k-\tau_{ji}(k)}^{k-1} x_j^T(l) Q_{ji} x_j(l) \right) \right. \\
&\quad \left. + \sum_{l=-\tau_{ji}+1}^0 \left(x_j^T(k) Q_{ji} x_j(k) \right. \right. \\
&\quad \left. \left. - x_j^T(k+l) Q_{ji} x_j(k+l) \right) \right\} \\
&\leq \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \left(\sum_{l=k+1-\tau_{ji}}^k x_j^T(l) Q_{ji} x_j(l) \right. \\
&\quad \left. - x_j^T(k-\tau_{ij}(k)) Q_{ji} x_j(k-\tau_{ij}(k)) \right. \\
&\quad \left. + \tau_{ji} x_j^T(k) Q_{ji} x_j(k) \right. \\
&\quad \left. - \sum_{l=k-\tau_{ij}+1}^k x_j^T(l) Q_{ji} x_j(l) \right)
\end{aligned}$$

$$\begin{aligned}
&= \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \left(\tau_{ji} x_j^T(k) Q_{ji} x_j(k) \right. \\
&\quad \left. - x_j^T(k-\tau_{ji}(k)) Q_{ji} x_j(k-\tau_{ji}(k)) \right) \\
&= \sum_{i=1}^n \sum_{j \in \mathcal{S}(i)} \left(\tau_{ij} x_i^T(k) Q_{ij} x_i(k) \right. \\
&\quad \left. - x_i^T(k-\tau_{ij}(k)) Q_{ij} x_i(k-\tau_{ij}(k)) \right), \\
\Delta V_3(k) &= \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \left(x_j^T(k) R_{ji} x_j(k) - x_j^T(k-\tau_{ji}) R_{ji} x_j(k-\tau_{ji}) \right) \\
&= \sum_{i=1}^n \sum_{j \in \mathcal{S}(i)} \left(x_i^T(k) R_{ij} x_i(k) - x_i^T(k-\tau_{ij}) R_{ij} x_i(k-\tau_{ij}) \right), \\
\Delta V_4(k) &= \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \left(\tau_{ji} \eta_j^T(k) Z_{ji} \eta_j(k) - \sum_{l=k-\tau_{ji}}^{k-1} \eta_j^T(l) Z_{ji} \eta_j(l) \right) \\
&= \sum_{i=1}^n \sum_{j \in \mathcal{S}(i)} \left(\tau_{ij} \eta_i^T(k) Z_{ij} \eta_i(k) - \sum_{l=k-\tau_{ij}}^{k-1} \eta_i^T(l) Z_{ij} \eta_i(l) \right).
\end{aligned} \tag{A.5}$$

Since

$$\begin{aligned}
&= - \sum_{l=k-\tau_{ij}}^{k-1} \eta_i^T(l) Z_{ij} \eta_i(l) \\
&= - \sum_{l=k-\tau_{ij}(k)}^{k-1} \eta_i^T(l) Z_{ij} \eta_i(l) - \sum_{l=k-\tau_{ij}}^{k-\tau_{ij}(k)-1} \eta_i^T(l) Z_{ij} \eta_i(l),
\end{aligned} \tag{A.6}$$

and from Lemma 1, we get

$$\begin{aligned}
&= - \sum_{l=k-\tau_{ij}(k)}^{k-1} \eta_i^T(l) Z_{ij} \eta_i(l) \\
&\leq - \frac{1}{\tau_{ij}(k)} \left[x_i^T(k) - x_i^T(k-\tau_{ij}(k)) \right] \\
&\quad \times Z_{ij} \left[x_i(k) - x_i(k-\tau_{ij}(k)) \right], \\
&= - \sum_{l=k-\tau_{ij}}^{k-\tau_{ij}(k)-1} \eta_i^T(l) Z_{ij} \eta_i(l) \\
&\leq - \frac{1}{\tau_{ij}-\tau_{ij}(k)} \left[x_i^T(k-\tau_{ij}(k)) - x_i^T(k-\tau_{ij}) \right] Z_{ij} \\
&\quad \times \left[x_i(k-\tau_{ij}(k)) - x_i(k-\tau_{ij}) \right].
\end{aligned} \tag{A.7}$$

Thus, from Lemma 2, it yields that

$$\begin{aligned}
& - \sum_{l=k-\tau_{ij}}^{k-1} \eta_i^T(l) Z_{ij} \eta_i(l) \\
& \leq -\frac{1}{\tau_{ij}} \begin{bmatrix} x_i(k) - x_i(k - \tau_{ij}(k)) \\ x_i(k - \tau_{ij}(k)) - x_i(k - \tau_{ij}) \end{bmatrix}^T \begin{bmatrix} Z_{ij} & T_{ij} \\ * & Z_{ij} \end{bmatrix} \\
& \times \begin{bmatrix} x_i(k) - x_i(k - \tau_{ij}(k)) \\ x_i(k - \tau_{ij}(k)) - x_i(k - \tau_{ij}) \end{bmatrix}. \tag{A.8}
\end{aligned}$$

On the other hand, for any matrices M_{i1} , M_{i2} , and $U_{ij} = U_{ij}^T > 0$ with appropriate dimensions, it follows that

$$\begin{aligned}
0 &= 2 \sum_{i=1}^n \left[x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2} \right] \\
& \times \left[\eta_i(k) - B_i K_i x_i(k) - \sum_{j \in \mathcal{P}(i)} B_{dji} K_j x_j(k - \tau_{ji}(k)) \right] \\
& \leq 2 \sum_{i=1}^n \left[x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2} \right] [\eta_i(k) - B_i K_i x_i(k)] \\
& + \sum_{i=1}^n \sum_{j \in \mathcal{P}(i)} \left([x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2}] \right. \\
& \quad \times U_{ji} [x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2}]^T \\
& \quad + x_j^T(k - \tau_{ji}(k)) K_j^T B_{dji}^T \\
& \quad \times U_{ji}^{-1} B_{dji} K_j x_j(k - \tau_{ji}(k)) \Big) \\
& = 2 \sum_{i=1}^n \left[x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2} \right] [\eta_i(k) - B_i K_i x_i(k)] \\
& + \sum_{i=1}^n \left([x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2}] \right. \\
& \quad \times \left(\sum_{l \in \mathcal{P}(i)} U_{li} \right) [x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2}]^T \\
& \quad + \sum_{l \in \mathcal{P}(i)} x_j^T(k - \tau_{ji}(k)) \\
& \quad \times K_j^T B_{dji}^T U_{ji}^{-1} B_{dji} K_j x_j(k - \tau_{ji}(k)) \Big)
\end{aligned}$$

$$\begin{aligned}
& = \sum_{i=1}^n \sum_{j \in \mathcal{S}(i)} \left\{ \frac{1}{m_i} \right. \\
& \quad \times \left(2 [x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2}] \right. \\
& \quad \times [\eta_i(k) - B_i K_i x_i(k)] \\
& \quad + [x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2}] \left(\sum_{l \in \mathcal{P}(i)} U_{li} \right) \\
& \quad \times [x_i^T(k) M_{i1} + \eta_i^T(k) M_{i2}]^T \Big) \\
& \quad + x_i^T(k - \tau_{ij}(k)) K_i^T B_{dij}^T U_{ij}^{-1} \\
& \quad \times B_{dij} K_i x_i(k - \tau_{ij}(k)) \Big\}. \tag{A.9}
\end{aligned}$$

So, combining (A.4)–(A.9), we get that

$$\Delta V(k) \leq \sum_{i=1}^n \sum_{j \in \mathcal{S}(i)} \zeta_{ij}^T(k) \Psi_{ij} \zeta_{ij}(k), \tag{A.10}$$

where

$$\begin{aligned}
\zeta_{ij}(k) &= [x_i^T(k) \quad x_i^T(k - \tau_{ij}(k)) \quad x_i^T(k - \tau_{ij}) \quad \eta_i^T(k)]^T, \\
\Psi_{ij} &= \begin{bmatrix} \Phi_{ij}^{11} & \frac{1}{\tau_{ij}} (Z_{ij} - T_{ij}) & \frac{1}{\tau_{ij}} T_{ij} & \Phi_{ij}^{14} \\ * & \Psi_{ij}^{22} & \frac{1}{\tau_{ij}} (Z_{ij} - T_{ij}) & 0 \\ * & * & -R_{ij} - \frac{1}{\tau_{ij}} Z_{ij} & 0 \\ * & * & * & \Phi_{ij}^{44} \end{bmatrix}, \\
\Psi_{ij}^{22} &= \Phi_{ij}^{22} + K_i^T B_{dij}^T U_{ij}^{-1} B_{dij} K_i. \tag{A.11}
\end{aligned}$$

From the Schur complement, it is known that the globally asymptotical stability of system (7) can be guaranteed if (12) and (13) hold for any $i \in \mathcal{N}$ and $j \in \mathcal{S}(i)$.

Thus, the proof is completed. $\square$

Acknowledgments

This work was supported by the National High Technology Research and Development Programme of China (863 Programme) under Grant 2009AA012201, the National Natural Science Foundation of China under Grant 61174085, the Training Excellent Young Teachers in Shanghai Universities (B37-0109-10-008), the Shanghai University Innovation Foundation (Grant no. A.10-0109-10-014), and the Industry-University-Research Project of Shanghai.

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