Stabilization Control Design for Network Switched System with Communication Constrains

Yi Liu[1], Yuheng Pan[1](✉), Weijia Lu[1], and Zhiyan Xue[2]

[1] School of Computer and Information Engineering, Tianjin Chengjian University, Tianjin 300384, China
yuheng0616@sina.com

[2] School of Electronic Information Engineering, Suzhou Vocational University, Suzhou 215006, Jiangsu, China

Abstract. Switching laws based on average dwell time method and switched state feedback controller are designed for a network switched control system with communication constrains. The networked control system is modeled as a discrete-time switched system with time delay and parametric uncertainties. If feedback control access rate is higher than the stability condition, then the designed scheduling strategy can guarantee every subsystem reaches exponential stability. Sufficient condition for exponentially stability is also presented, and the result shows systems can be stabilized under the designed switch laws. Finally, the effectiveness of the proposed approaches is demonstrated through MATLAB simulation.

Keywords: Communication constrains · Average dwell time
Exponential stability · Network control

1 Introduction

The network control system (NCS) is a closed-loop control system composed of controller, actuator and communication network, which applies network communication to the decentralized control system and achieve resource sharing and remote operation. Therefore it can meet requirement of large-scale and complicated systems. Therefore this control method has a promising future and will be an important tendency for the control systems [1]. However for practical systems, controllers cannot manage the whole objects all along due to the constraint of the equipment and resources. So in the limited communication network partial subsystems remain open-loop condition at the same time. This question can be described as the medium communication constrains (MCC) [2–6].

To achieve stable control, an appropriate switched strategy is designed for the switched system, so NCS can be analyzed using switched method [7–11]. The average dwell time is one of the most effective methods, therefore a new dynamic scheduling strategy and feedback control designing method based on mode-dependent average dwell time is proposed in the literature [12]. The system is modeled as a discrete

C. Li and S. Mao (Eds.): WiCON 2017, LNICST 230, pp. 461–470, 2018.
https://doi.org/10.1007/978-3-319-90802-1_41

switched system with uncertain parameters. This method not only considers the influence caused by random short time delay but also presents the average dwell time conditions of all the subsystems. The existing research about the network control of MCC is focused on constrains of media access, digit ratio and information ratio. In the literature [13], the NCS with fixed time delay is modeled as discrete switched system with uncertain parameters and under quantizers are modeled as multiple modals the MEF-TOD (Maximum Error First-Try Once Discard) dispatch strategy. And then according to Lyapunov theory the digit ratio conditions that enable quantization errors convergent can be verified. Aiming at the random-delay NCS with MCC, a design method based on the TOD dynamic dispatch strategy and state feedback controller is presented in the literature [14]. While the literature [15] presents a technique using TOD dynamic dispatch strategy and H∞ quantization control, which manages errors using sector bound approach and models the close-loop NCS as discrete switched system with uncertain parameters. The uncertain network-induced time delay is modeled as polytope-type uncertainty in the literature [16]. In this system the robust control method based on the parameter-correlated Lyapunov stability is used to design network discrete controller and simultaneously adopt control and dispatch to ensure the stability of every subsystem in NCS. For the NCS with delay and parameter uncertainty under the MCC few scholar researches non-linear network switch system using average swell time switch law.

This paper researches the stability of NCS with communication constrains utilizing average swell time method. The state feedback controller and the average swell time condition, which assures the system exponential stable, are presented in the form of linear matrix inequation using Lyapunov function. Finally, the effectiveness of the proposed approaches is demonstrated through MATLAB simulation.

2 Problem Statement

If the state equation of NCS is of the form

$$x(t) = A_p x(t) + B_p u(t) \tag{1}$$

where, $x(t) \in R^n$, $u(t) \in R^m$ are respectively the state variable and the input of the controlled object. A_p and B_p are the optimal dimensional matrixes.

The structure diagram of NCS is shown in Fig. 1. The controlled object is composed of umpty sensors and actuators. The network-induced time delay between sensors and controllers is τ_k^{sc} while the one between actuators and controllers is τ_k^{ca}. Suppose the system satisfies with the following terms.

Hypothesis 1: Sensors are time-driven and the sampling period is h, controllers and actuators are both event-driven.
Hypothesis 2: $\tau_k = \tau_k^{sc} + \tau_k^{ca}$ is time-varying and $0 < \tau_k < h$.
Hypothesis 3: All signals from sensors or controllers cannot be transferred simultaneously because of the restrictions of network bandwidth. The transferred

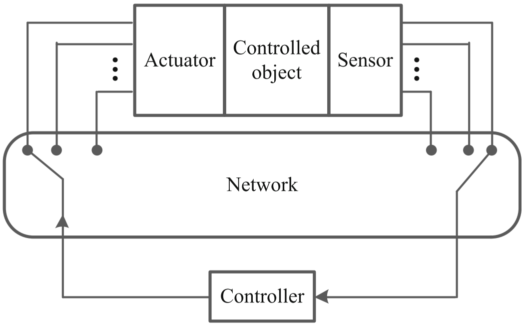

Fig. 1. The structure diagram of NCS

numbers of state vector and control signal every time are $d_s(0 < d_s \le n)$ and $d_c(0 < d_c \le m)$ respectively.

Discrete the state equation of the controlled objects

$$x(k+1) = Ax(k) + B_0(\tau_k)\hat{u}(k) + B_1(\tau_k)\hat{u}(k-1) \tag{2}$$

where, $A = e^{A_p h}$, $B_0(\tau_k) = \int_0^{h-\tau_k} e^{A_p t} B dt$

Because of network restrain in the hypothesis 3, the scheduling network nodes are required in every transmission. Introduce the sensor-control scheduling vectors $\theta(k)$ and the control-actuator ones $\delta(k)$ and then

$$\theta_i(k) = \begin{cases} 1, & \text{if } x_i(k) \text{ is transmitted} \\ 0, & \text{otherwise} \end{cases} \quad i \in (1, 2, \ldots, n) \tag{3}$$

$$\delta_i(k) = \begin{cases} 1, & \text{if } u_i(k) \text{ is transmitted} \\ 0, & \text{otherwise} \end{cases} \quad i \in (1, 2, \ldots, m) \tag{4}$$

During the kth sampling period, the sensors and control nodes allowed to transmit are respectively determined by the scheduling vector $\theta(k) = [\theta_1(k), \theta_2(k), \ldots, \theta_n(k)]$ and $\delta(k) = [\delta_1(k), \delta_2(k), \ldots, \delta_m(k)]$.

Define $\Lambda(k) = diag(\theta(k))$, and then the effective updated data received by the control nodes are $\Lambda(k)x(k)$, while the data that are not updated hold the last value through the zero-order holder (ZOH). So the input of the controller is as follows

$$\hat{x}(k) = \Lambda(k)x(k) + (\mathrm{I} - \Lambda(k))\hat{x}(k-1) \tag{5}$$

Similarly, define $\Pi(k) = diag(\delta(k))$ and then the output is

$$\hat{u}(k) = \Pi(k)u(k) + (\mathrm{I} - \Pi(k))\hat{u}(k-1) \tag{6}$$

The total numbers of sensors and actuators are n and m respectively in this NCS, but only d_s sensors and d_c actuators are allowed to transmit data. Take each scheme as a modality, and the system provides N types of modality.

Where, $N = [n!/(n-d_s)!] \times [m!/(m-d_c)!]$

Each modality corresponds to a group of $\Lambda_i(k)$ and $\Pi_i(k)$, $(i = 1, 2, \ldots, N)$. So the generalized discrete modal of NCS is as follows

$$\begin{cases} x(k+1) = Ax(k) + B_0(\tau_k)\hat{u}(k) + B_1(\tau_k)\hat{u}(k-1) \\ \hat{x}(k) = \Lambda_i(k)x(k) + (\mathrm{I} - \Lambda_i(k))\hat{x}(k-1) \\ \hat{u}(k) = \Pi_i(k)u(k) + (\mathrm{I} - \Pi_i(k))\hat{u}(k-1) \end{cases} \tag{7}$$

The system includes N types of modality, i.e. N subsystems, which are switched using TOD strategy.

Define $s_i(k) = [\theta_i(k), \delta_i(k)]$ and $s_i(k) \in \{0, 1\}^{n+m}$, $i = 1, 2, \ldots, N$, $s_i(k)$ indicates ith modality of the system during kth sapling period.

Let $\Gamma_i = diag(s_i(k))$, i.e. $\Gamma_i = diag(s_i(k))$, then the errors are as follows

$$e(k) = \begin{bmatrix} e^x(k) \\ e^u(k) \end{bmatrix} = \begin{bmatrix} x(k) - \hat{x}(k-1) \\ u(k) - \hat{u}(k-1) \end{bmatrix} \tag{8}$$

According to TOD dynamic scheduling algorithm, the switch function is $\sigma = \arg max\{\Gamma_1(k)e(k), \Gamma_2(k)e(k), \ldots, \Gamma_N(k)e(k)\}$, $\sigma \in \{1, 2, \ldots, N\}$ where arg is subscript function, $\Gamma_i(k)(i = 1, 2, \ldots, N)$ corresponds the ith modality.

The form of the designed discrete state feedback controller is

$$u(k) = K_\sigma \hat{x}(k) \tag{9}$$

where, $\hat{x}(k) \in R^n$, $u(k) \in R^m$ are respectively the input and output of the controller. K_σ is the state feedback gain after introducing TOD scheduling strategy.

From hypothesis 2, $\tau_k \in [0, h]$ varies randomly. $B_0(\tau_k)$ and $B_1(\tau_k)$ are also time varying, then

$$\begin{aligned} B_0(\tau_k) &= B_0 + DF(\tau'_k)E \\ B_1(\tau_k) &= B_1 - DF(\tau'_k)E \end{aligned} \tag{10}$$

where, $\tau'_k \in [-h/2, h/2]$.

Suppose $\bar{F}(\tau'_k) = \int_0^{-\tau'_k} e^{A_p t} dt$, $\beta = max \int_0^{-\tau'_k} e^{A_p t} dt = \int_{h/2}^{h} e^{A_p t} dt$ then $B_0 = \int_0^{h/2} e^{A_p t} B_p dt$, $B_1 = \int_{h/2}^{h} e^{A_p t} B_p dt$, $D = \beta e^{A_p (h/2)}$, $E = B_p$ are both constant matrixes, $F(\tau'_k) = \beta^{-1} \bar{F}(\tau'_k)$ changes with τ_k, and $F^T(\tau'_k) F(\tau'_k) \leq I$.

Let $z(k) = [x^T(k)\hat{x}^T(k-1)\hat{u}^T(k-1)]$, then the equation of the close-loop control is as follows

$$z(k+1) = \Phi_\sigma z(k) \quad \sigma \in \{1, 2, \ldots, N\} \tag{11}$$

where

$$\Phi_\sigma = \begin{bmatrix} a_1 & b_1 & c_1 \\ \Lambda_\sigma & I - \Lambda_\sigma & 0 \\ \Pi_\sigma K_\sigma \Lambda_\sigma & \Pi_\sigma K_\sigma (I - \Lambda_\sigma) & I - \Pi_\sigma \end{bmatrix}$$
$$= \mathrm{G}_\sigma + H\Pi_\sigma K_\sigma \Lambda_\sigma + D_0 F\left(\tau'_k\right) E\Pi_\sigma (K_\sigma \Lambda_\sigma - I)$$

$$a_1 = A + B_0(\tau_k)\Pi_\sigma K_\sigma \Lambda_\sigma$$

$$b_1 = B_0(\tau_k)\Pi_\sigma K_\sigma (I - \Lambda_\sigma)$$

$$c_1 = B_0(\tau_k)(I - \Pi_\sigma) + B_1(\tau_k)$$

$$G_\sigma = \begin{bmatrix} A & 0 & B_0(I - \Pi_\sigma) + B_1 \\ \Lambda_\sigma & I - \Lambda_\sigma & 0 \\ 0 & 0 & I - \Pi_\sigma \end{bmatrix}$$

$$H = \begin{bmatrix} B_0 \\ 0 \\ I \end{bmatrix}, \ D_0 = \begin{bmatrix} D \\ 0 \\ 0 \end{bmatrix}, \ \Lambda_\sigma = \begin{bmatrix} \Lambda_\sigma \\ I - \Lambda_\sigma \\ 0 \end{bmatrix}^T, \ \bar{I} = \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix}^T \quad \sigma \in \{1, 2, \ldots, N\}$$

Definition 1 [17]**.** In any time $t_2 > t_1 \geq 0$, $N_r(t_1, t_2)$ means the switch times during $[t_1, t_2]$. If there is $T_\alpha > 0$, $N_0 \geq 0$, which can satisfy the following inequality

$$N_r(t_1, t_2) \leq N_0 + \frac{t_2 - t_1}{\mathrm{T}_\alpha} \tag{12}$$

T_α is average swell time, N_0 is buffering boundary.

Lemma 1 [18]**.** H, E and I are the optimal dimensional matrixes and Q is symmetric matrix. For all the matrixes satisfy with $F_{ri}(k)^{\mathrm{T}} F_{ri}(k) \leq I$, when $\varepsilon \geq 0$, $Q + \varepsilon^2 HH^T + \varepsilon^{-2} E^T E \leq 0$, then $Q + HF_{ri}(k)E + E^T F_{ri}(k)^T H^T \leq 0$.

3 Main Results

Theorem 1. The positive definite matrix P and constant $\lambda \in (0, 1)$ satisfies the matrix inequality

$$\begin{bmatrix} -P^{-1} + \varepsilon_\sigma D_0 D_0^T & * & * \\ \mathrm{G}_\sigma P^{-1} + H\Pi_\sigma K_\sigma \Lambda_\sigma P^{-1} & -(1 - \lambda)P & * \\ 0 & E\Pi_\sigma (K_\sigma \Lambda_\sigma - I)P^{-1} & -\varepsilon_\sigma I \end{bmatrix} < 0 \tag{13}$$

If the visiting rate and frequency are

$$\frac{\alpha_c(k)}{k} \geq \frac{\ln \lambda_o - \ln \lambda^*}{\ln \lambda_o - \lambda_c} \tag{14}$$

$$\begin{aligned} &N(k) \leq N_0 + k/\mathrm{T}_\alpha,\ N_0 = \frac{\ln c}{\ln \mu}, \\ &\mathrm{T}_\alpha > \mathrm{T}_\alpha^* = \frac{\ln \mu}{2\ln \rho - \ln \lambda^*} \end{aligned} \tag{15}$$

then there are feedback controllers (13) to make the system expressed by Eq. (1) stable, and the estimated state of the system is $\|x(k)\| \leq \sqrt{\frac{bc}{a}}\rho^k \|x(0)\|$. Where, * represents the transposition of the symmetric position, $0 < \lambda_c < 1$, $\lambda_o > 1$ are the feedback coefficients of close-loop and open-loop respectively, T_α is the average swell time. $\lambda_c < \lambda^* < \rho^2 < 1$, $c > 0$ and $V_c(k) \leq \mu V_o(k)$, $V_o(k) \leq \mu V_c(k)$.

Proof. The piecewise quadratic Lyapunov-like function is as follows

$$V(k) = \begin{cases} V_c(k), & close - loop \\ V_o(k), & open - loop \end{cases} \tag{16}$$

If $V_c(k) = z^T(k)Pz(k)$, then

$$\begin{aligned} &\Delta V_c(k) + \lambda_c V_c(k) \\ &= z^T(k+1)Pz(k+1) - z^T(k)Pz(k) + \lambda_c V_c(k) \\ &= z^T(k)\Phi_\sigma^T P \Phi_\sigma z(k) - z^T(k)Pz(k) + \lambda_c V_c(k) \\ &= z^T(k)\left(\Phi_\sigma^T P \Phi_\sigma - P + \lambda_c P\right)z(k) \\ &= z^T(k)\begin{bmatrix} -P^{-1} & \Phi_\sigma \\ \Phi_\sigma^T & -(1-\lambda_c)P \end{bmatrix} z(k) \end{aligned}$$

According to Schur complement lemma and the above equations, $\Delta V_c(k) + \lambda_c V_c(k) < 0$. Similarly, the above conclusion is tenable for the open-loop system. So

$$\begin{aligned} V_c(k+1) \leq \lambda_c V_c(k) \\ V_o(k+1) \leq \lambda_o V_o(k) \end{aligned} \tag{17}$$

Suppose during the time interval $[k_{2j}, k_{2j+1})$, $j = 0, 1, 2, \ldots$, the system control channel is close-loop, while during the time interval $[k_{2j+1}, k_{2j+2})$, $j = 0, 1, 2, \ldots$ it is open-loop. For any $k > 0$, according to the Eq. (17),

$$V(k) \leq \begin{cases} \lambda_c^{k-k_{2j}} V_c(k_{2j}), & k_{2j} \leq k < k_{2j+1} \\ \lambda_o^{k-k_{2j+1}} V_o(k_{2j+1}), & k_{2j+1} \leq k < k_{2j+2} \end{cases} \tag{18}$$

So when $k \in \left[k_{2j+1}, k_{2j+2}\right)$, according to the Eq. (18) and definition

$$\begin{aligned} V(k) &\le \lambda_o^{k-k_{2j+1}} V_o\left(k_{2j+1}\right) \\ &\le \mu \lambda_o^{k-k_{2j+1}} V_o\left(k_{2j+1}\right) \\ &\le \mu \lambda_o^{k-k_{2j+1}} \lambda_c^{k_{2j+1}-k_{2j}} V_o\left(k_{2j+1}\right) \\ &\le \ldots \\ &\le \mu^{N(k)} \lambda_c^{\alpha_c(k)} \lambda_o^{k-\alpha_c(k)} V(0) \end{aligned}$$

Similarly when $k \in \left[k_{2j}, k_{2j+1}\right)$,

$$V(k) \le \mu^{N(k)} \lambda_c^{\alpha_c(k)} \lambda_o^{k-\alpha_c(k)} V(0) \tag{19}$$

According to the Eq. (19),

$$(\ln \lambda_0 - \ln \lambda_c)\alpha_c(k) \ge (\ln \lambda_0 - \ln \lambda^*)k$$

Namely

$$\lambda_c^{\alpha_c(k)} \lambda_0^{\mathrm{k}-\alpha_c(k)} \le (\lambda^*)^k \tag{20}$$

According to the Eq. (20),

$$\mu^{N(k)} \le \mu^{N_0 + \frac{k}{T_\alpha}} \le \mu^{N_0} \mu^{\frac{k(2\ln\rho - \ln\lambda^*)}{\ln \mu}} = c\left(\frac{\rho^2}{\lambda^*}\right)^k$$

From Eqs. (16), (19) and (20) $V(k) \le c\rho^{2k} V(0)$

Because of quadratic form Lyapunov-like function, then the constants $a_c > 0, a_0 > 0, b_c > 0, b_0 > 0$ make the following inequation established.

$$\begin{aligned} a_c x(k)^2 \le V_c(k),\ a_o x(k)^2 \le V_o(k) \\ V_c(0) \le b_c x(0)^2,\ V_o(0) \le b_o x(0)^2 \end{aligned} \tag{21}$$

Then

$$a x(k)^2 \le V(k),\ V(0) \le b x(0)^2 \tag{22}$$

where $a = \min\{a_c, a_o\}$, $b = \min\{b_c, b_o\}$.

Finally, according to Eqs. (21) and (22),

$$x(k) \le \sqrt{\frac{bc}{a}} \rho^k x(0)$$

Due to the uncertain item in Φ_σ, transform $\begin{bmatrix} -P^{-1} & \Phi_\sigma \\ \Phi_\sigma^T & -(1-\lambda)P \end{bmatrix}$ into

$$\begin{bmatrix} -P^{-1} & \Phi_\sigma \\ \Phi_\sigma^T & -(1-\lambda)P \end{bmatrix} = \begin{bmatrix} -P^{-1} & \mathrm{G}_\sigma + H\Pi_\sigma K_\sigma \Lambda_\sigma \\ * & -(1-\lambda)P \end{bmatrix} +$$
$$\begin{bmatrix} D_0 \\ 0 \end{bmatrix} F(\tau_k') \begin{bmatrix} 0 \\ E\Pi_\sigma(K_\sigma\Lambda_\sigma - I) \end{bmatrix}^T + \begin{bmatrix} 0 \\ E\Pi_\sigma(K_\sigma\Lambda_\sigma - I) \end{bmatrix} F^T(\tau_k') \begin{bmatrix} D_0 \\ 0 \end{bmatrix}^T$$

According to the lemma, further transform the above equation into

$$\begin{bmatrix} -P^{-1} & \mathrm{G}_\sigma + H\Pi_\sigma K_\sigma \Lambda_\sigma \\ * & -(1-\lambda)P \end{bmatrix} + \varepsilon_\sigma \begin{bmatrix} D_0 \\ 0 \end{bmatrix} \begin{bmatrix} D_0 \\ 0 \end{bmatrix}^T$$
$$+ \varepsilon_\sigma^{-1} \begin{bmatrix} 0 \\ E\Pi_\sigma(K_\sigma\Lambda_\sigma - I) \end{bmatrix} \begin{bmatrix} 0 \\ E\Pi_\sigma(K_\sigma\Lambda_\sigma - I) \end{bmatrix}^T$$

$$+ \begin{bmatrix} -P^{-1} + \varepsilon_\sigma D_0 D_0^T & * & * \\ \mathrm{G}_\sigma + H\Pi_\sigma K_\sigma \Lambda_\sigma & -(1-\lambda)P & * \\ 0 & E\Pi_\sigma(K_\sigma\Lambda_\sigma - I) & -\varepsilon_\sigma I \end{bmatrix}$$

Let $X = P^{-1}$, multiply it by $diag(I, X, I)$ in both left and right sides, the above equation can be changed into the equation in the theorem. So the system can be exponent stability.

4 Simulation Example

Consider the equation of NCSs $x(t) = A_p x(t) + B_p u(t)$, where $\mathrm{A_p} = \begin{bmatrix} -0.8 & -0.01 \\ 1 & 0.1 \end{bmatrix}$, $\mathrm{B_p} = \begin{bmatrix} 0.4 \\ 0.1 \end{bmatrix}$

And in the Eq. (2),

$A = \begin{bmatrix} 0.852 & -0.0019 \\ 0.1867 & 1.02 \end{bmatrix}$, $B_0 = \begin{bmatrix} 0.0384 \\ 0.0032 \end{bmatrix}$, $B_1 = \begin{bmatrix} 0.0355 \\ 0.0055 \end{bmatrix}$, $D = \begin{bmatrix} 0.0355 & 0 \\ 0.0037 & 0.0389 \end{bmatrix}$, $E = \begin{bmatrix} 0.4 \\ 0.1 \end{bmatrix}$

The system includes one control input and two states. When $d_s = d_c = 1$, the system have two types of modals, i.e. $s_1 = [1 \quad 0 \quad 1]$ and $s_2 = [0 \quad 1 \quad 1]$. Use Matlab the LMI (Linear Matrix Inequality) in theorem can be solved.

$$K_1 = [-1.1065 \quad 0.11577]$$
$$\mathrm{K}_2 = [-0.0169 \quad -1.3888]$$

Suppose that the time delay is the random number within (0, 0.1) and the original state is $[0.3, -0.3]^{\mathrm{T}}$. The state response curve of the above network switch control system is shown in Fig. 2.

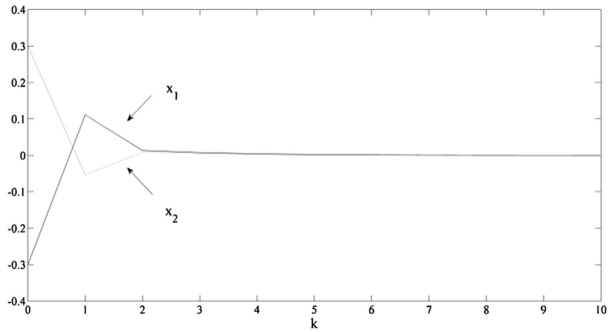

Fig. 2. Response of state curve

As shown in the Fig. 2, the system can be stable with the designed controller and switch laws.

5 Conclusions

In conclusion, the stability control of network switch system with MCC is researched. The switch laws are designed using the average dwell time method and the conditions to ensure the system exponential stability. The results show the system can be stable if the visiting rate of a feedback control system is greater than a value.

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