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Stability of networked control systems with communication constraints

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Abstract: Considering the constraints of network bandwidth, multiple-packet transmission was adopted here in the networked control system (NCS). To avoid the wrong order of these network packets, only one packet of the plant measurements could be transmitted at a time. Based on the assumption, the NCS was modeled as an asynchronous dynamical system (ADS). In the multiple-packet transmission NCS, there were also long network-induced delays, which would degrade the performance of the NCS, and could even destabilize the system. To guarantee the system's stability, Lyapunov stability theory of ADS was applied to get the sufficient conditions on the stability of the NCS with multiple-packet transmission and long time delays. The simulated experimental results show that the proposed approach is efficient.

Key words: networked control system (NCS); asynchronous dynamical systems; Lyapunov; stability

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具有通信约束的网络控制系统稳定性研究

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摘要:针对网络带宽的限制,在网络控制系统中需要采用多包传输.为了避免这些网络包发生时序错乱,每次只传输控制对象测量值分出的多个数据包中的一个,从而将这类网络控制系统建模为异步动态系统.多包传输网络控制系统中同样存在大的网络延时,这必将影响系统的控制性能,甚至使系统失稳.为了保证这类系统的稳定性,借助异步动态系统的 Lyapunov 稳定理论,给出了多包传输长时延网络控制系统的 Lyapunov 稳定条件.仿真实验结果表明了该方法的有效性.

关键词:网络控制系统(NCS);异步动态系统;Lyapunov;稳定性

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0 Introduction

Networked control systems (NCSs) are feedback control loops closed through a real time network, that is, in NCSs, communication networks are employed to exchange information and control signals (reference input, plant output, control input, etc.) between control system components (sensors, controllers, actuators, etc.)[1]. The main advantages of NCSs are low cost, reduced weight, simple installation and maintenance, and high reliability. As a result, NCSs have great potential for applications in manufacturing plants, vehicles, aircraft, and spacecrafts[2].

Despite their advantages and potentials, communication networks in control loops make the analysis and design of a networked control system (NCS) complicated. When we design an NCS, a new constraint, the limited bandwidth of the communication network, must be considered. Sometimes, all the data packets containing the plant measurements may not be permitted to be transmitted because of communication constraints, which may deteriorate the system performance and even cause system instability[3, 4]. The problem of stabilization with finite communication bandwidth was introduced in Ref. [5, 6] and further pursued in Ref. [7, 8]. A dwell-time switching method to reduce the data rate of the network was proposed in Ref. [9]. Ref. [10, 11] introduced signal quantization into the design of the systems and thus reduced the data rate. A new framework for distributed control systems was introduced in Ref. [12], which used estimators at each node to achieve a significant savings in the required bandwidth. Recent relevant works focus on analysis of networked control systems with multiple-packet transmission[13~15], but the results of these works are all based on the assumption that the network-induced delays are less than one sampling period. In fact, the network-induced delays are usually more than one sampling period, which makes the system analysis much more complex. Therefore, it is necessary to study this case further.

1 Modeling of an NCS

Time delays in NCS can be in general divided into two main groups: computation delays and network delays. We only consider the network delays in this paper, because the effect of computation delays is always deterministic and its occurrence can be taken into account in a control algorithm directly. The detailed assumptions are described as follows.

(Ⅰ) The sensor node is time driven, with a sampling period h, and transmits each packet based on a static scheduling algorithm (say profibus, token ring), which means that only one packet of the plant measurements can be transmitted at a time, and that the controller receives these packets sequentially.

(Ⅱ) Both the controller and actuator nodes are event driven, which means that the controller calculates the control data as soon as the control data is available.

(Ⅲ) For analysis purposes, we only consider the sensor-to-controller delay $\tau(h<\tau<lh, l\geqslant 2$, l is a certain integer), and the lengths of the past are known to the controller by using the timestamp technique.

(Ⅳ) There are no data dropouts during the transmission on the communication network.

The multiple-packet transmission NCS with long delays is depicted in Fig. 1, where the controller is directly connected to the plant with communication channel.

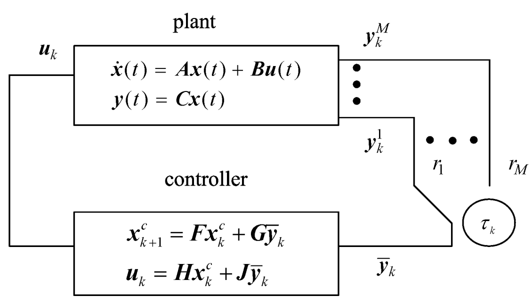

Fig. 1 Multiple-packet transmission NCS with long time delays

Consider the following continuous-time plant

$$\left.\begin{aligned}\dot{\boldsymbol{x}}(t) &= \boldsymbol{A}\boldsymbol{x}(t)+\boldsymbol{B}\boldsymbol{u}(t)\\ \boldsymbol{y}(t) &= \boldsymbol{C}\boldsymbol{x}(t)\end{aligned}\right\} \quad (1)$$

where $\boldsymbol{x}\in R^N$ is the plant state, $\boldsymbol{y}\in R^M$ is the plant output, $\boldsymbol{u}\in R^L$ is the plant input, and $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ are matrices of compatible dimensions. Sampling the plant with period h, we obtain [16]

$$\left.\begin{aligned}\boldsymbol{x}_{k+1} &= \Theta\boldsymbol{x}_k+\sum_{i=1}^{l}\Gamma_i(\tau_k)\boldsymbol{u}(k-i)\\ \boldsymbol{y}_k &= \boldsymbol{C}\boldsymbol{x}_k\end{aligned}\right\} \quad (2)$$

where $\Theta=\mathrm{e}^{\boldsymbol{A}h}$, $\Gamma_i=\int_{t_i^k}^{t_{i-1}^k}\mathrm{e}^{\boldsymbol{A}(h-s)}\mathrm{d}s\boldsymbol{B}$, $t_{-1}^k=h$, $t_l^k=0$.

The discrete controller is given by

$$\left.\begin{aligned}\boldsymbol{x}_{k+1}^c &= \boldsymbol{F}\boldsymbol{x}_k^c+\boldsymbol{G}\bar{\boldsymbol{y}}_k\\ \boldsymbol{u}_k &= \boldsymbol{H}\boldsymbol{x}_k^c+\boldsymbol{J}\bar{\boldsymbol{y}}_k\end{aligned}\right\} \quad (3)$$

where $\boldsymbol{x}_k^c\in R^I$ is the controller state, $\boldsymbol{u}_k\in R^L$ is the controller output, $\bar{\boldsymbol{y}}_k\in R^M$ is the most recent information of the plant output received by controller, and $\boldsymbol{F}$, $\boldsymbol{G}$, $\boldsymbol{H}$, $\boldsymbol{J}$ are matrices of compatible dimensions.

We consider the case that the plant output is split into M packets, that is, $\boldsymbol{y}_k=(\boldsymbol{y}_k^{1\mathrm{T}}\cdots\boldsymbol{y}_k^{M\mathrm{T}})^{\mathrm{T}}$, then $\bar{\boldsymbol{y}}_k=(\bar{\boldsymbol{y}}_k^{1\mathrm{T}}\cdots\bar{\boldsymbol{y}}_k^{M\mathrm{T}})^{\mathrm{T}}$, where

$$\bar{\boldsymbol{y}}_k^m=\begin{cases}\boldsymbol{y}_k^m, & \text{if the packet containing } \boldsymbol{y}_k^m \text{ is transmitted successfully}\\ \bar{\boldsymbol{y}}_{k-1}^m, & \text{otherwise}\end{cases}$$

So, $\bar{\boldsymbol{y}}_k$ can be expressed as

$$\bar{\boldsymbol{y}}_k=\boldsymbol{P}_m\boldsymbol{y}_k+\boldsymbol{Q}_m\bar{\boldsymbol{y}}_{k-1},\ m=1,2,\cdots,M \quad (4)$$

where $\boldsymbol{P}_m=\mathrm{diag}(p_{ii})$, $p_{mm}=1$, $p_{ii}=0$ $(i\neq m)$; $\boldsymbol{Q}_m=\mathrm{diag}(q_{ii})$, $q_{ii}=1$ $(i\neq m)$, $q_{mm}=0$.

Defining $\boldsymbol{z}_k=(\boldsymbol{x}_k^{\mathrm{T}}\quad \boldsymbol{x}_k^{c\mathrm{T}}\quad \bar{\boldsymbol{y}}_{k-1}^{\mathrm{T}}\quad \boldsymbol{u}_{k-1}^{\mathrm{T}}\quad \boldsymbol{u}_{k-l}^{\mathrm{T}})^{\mathrm{T}}$ as the augmented state vector, the augmented closed-loop system is

$$\boldsymbol{z}_{k+1}=\boldsymbol{\Phi}_m\boldsymbol{z}_k,\ m=1,2,\cdots,M \quad (5)$$

where

$$\begin{aligned}\boldsymbol{x}_{k+1} &= (\Theta+\Gamma_0\boldsymbol{J}\boldsymbol{P}_m\boldsymbol{C})\boldsymbol{x}_k+\Gamma_0\boldsymbol{H}\boldsymbol{x}_k^c+\Gamma_0\boldsymbol{J}\boldsymbol{Q}_m\bar{\boldsymbol{y}}_{k-1}+\\ &\quad \Gamma_1\boldsymbol{u}(k-1)+\cdots+\Gamma_l\boldsymbol{u}(k-l)\\ \boldsymbol{x}_{k+1}^c &= \boldsymbol{G}\boldsymbol{P}_m\boldsymbol{C}\boldsymbol{x}_k+\boldsymbol{F}\boldsymbol{x}_k^c+\boldsymbol{G}\boldsymbol{Q}_m\bar{\boldsymbol{y}}_{k-1}\\ \bar{\boldsymbol{y}}_k &= \boldsymbol{P}_m\boldsymbol{C}\boldsymbol{x}_k+\boldsymbol{Q}_m\bar{\boldsymbol{y}}_{k-1}\\ \boldsymbol{u}_k &= \boldsymbol{J}\boldsymbol{P}_m\boldsymbol{C}\boldsymbol{x}_k+\boldsymbol{H}\boldsymbol{x}_k^c+\boldsymbol{J}\boldsymbol{Q}_m\bar{\boldsymbol{y}}_{k-1}\\ \boldsymbol{u}_{k-1} &= \boldsymbol{u}_{k-1}\\ &\ \,\vdots\\ \boldsymbol{u}_{k-l} &= \boldsymbol{u}_{k-l}\end{aligned}$$

$$\boldsymbol{\Phi}_m=\begin{pmatrix}\Theta+\Gamma_0\boldsymbol{J}\boldsymbol{P}_m\boldsymbol{C} & \Gamma_0\boldsymbol{H} & \Gamma_0\boldsymbol{J}\boldsymbol{Q}_m & \Gamma_1 & \Gamma_2 & \cdots & \Gamma_{l-1} & \Gamma_l\\ \boldsymbol{G}\boldsymbol{P}_m\boldsymbol{C} & \boldsymbol{F} & \boldsymbol{G}\boldsymbol{Q}_m & 0 & 0 & \cdots & 0 & 0\\ \boldsymbol{P}_m\boldsymbol{C} & 0 & \boldsymbol{Q}_m & 0 & 0 & \cdots & 0 & 0\\ \boldsymbol{J}\boldsymbol{P}_m\boldsymbol{C} & \boldsymbol{H} & \boldsymbol{J}\boldsymbol{Q}_m & 0 & 0 & \cdots & 0 & 0\\ 0 & 0 & 0 & I & 0 & \cdots & 0 & 0\\ 0 & 0 & 0 & 0 & I & \cdots & 0 & 0\\ \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots\\ 0 & 0 & 0 & 0 & 0 & \cdots & I & 0\end{pmatrix},$$

$$m=1,2,\cdots,M$$

2 Stability analysis

The model (5) of multiple-packet transmission NCS with long time delays described above is a typical ADS (asynchronous dynamical system). The stability of this ADS has been studied in Ref. [17]. ADSs, like hybrid systems, are systems that incorporate continuous and discrete dynamics. The continuous dynamics are governed by differential or difference equations, whereas finite automata that are driven asynchronously by external discrete events with fixed rates govern the discrete dynamics.

Before proceeding, a basic stability definition from Ref. [17] is repeated here.

The asynchronous dynamical system is said to be exponentially stable if its trajectories satisfy

$$\lim_{k\to\infty}\alpha^k\|\boldsymbol{z}_k\|=0 \quad (6)$$

For some $\alpha>1$. The largest α is referred to the decay rate of the system. It is clear that exponential stability implies uniform asymptotic stability.

Using ADS, we can describe model (5) as follows

$$\boldsymbol{z}_{k+1}=\boldsymbol{\Phi}_m\boldsymbol{z}_k,\ m=1,2,\cdots,M$$

where $m=1,2,\cdots,M$ represents the set of discrete states, which has a corresponding set of rate $r_1,r_2,\cdots,r_M$. These rates represent the fraction of time in which each discrete state occurs. So, $\sum_{m=1}^{M}r_m=1$.

A result for exponential stability is derived as follows.

Theorem 2.1 If there exists a Lyapunov function $V,R^n\to R_+$, then

$$\beta_1 \| z \|^2 \leqslant V(z) \leqslant \beta_2 \| z \|^2 \tag{7}$$

where $\beta_{1,2} > 0$ and V satisfies the following conditions:

(Ⅰ) there exists $\alpha_i > 0$, $i = 1, 2, \cdots, M$, such that

$$V(z_{k+1}) - V(z_k) \leqslant (\alpha_i^{-2} - 1)V(z_k) \tag{8}$$

(Ⅱ) α_i satisfies

$$\prod_{i=1}^{M} \alpha_i^{r_i} > \alpha > 1 \tag{9}$$

where M is the number of discrete states of the system. Then the asynchronous dynamical system $z_{k+1} = \Phi_i z_k$, where Φ_i occurs with rates r_i, $i=1,2,\cdots, M$, is exponentially stable in the sense of definition (6).

Proof Suppose that the discrete state transitions of any trajectory of the system occur at times $0=t_1<t_2<t_3<\cdots$. Then, for $t \in [t_k, t_{k+1}]$, condition (8) gives

$$V(z(t_{k+1})) \leqslant \alpha_i^{-2} V(z(t_k))$$

or

$$\ln V(z(t_{k+1})) \leqslant -2\ln \alpha_i + \ln V(z(t_k)) \tag{10}$$

Note that whenever a discrete state of the asynchronous dynamical system occurs we have a contributing term α_i on the right-hand side of equation (10). Hence, summing up these inequalities for $k=1,2,\cdots,K-1$, in the limit, the total time in which one discrete state occurs is equal to $r_i K$ as $K \to \infty$. Therefore

$$\ln V(z(K)) - \ln V(z(0)) \leqslant$$
$$-2\tilde{r}_1 K \ln \alpha_1 - 2\tilde{r}_2 K \ln \alpha_2 - \cdots - 2\tilde{r}_{MN} K \ln \alpha_{MN}$$

or by condition (9)

$$\ln V(z(K)) - \ln V(z(0)) < -2K \ln \alpha$$

So that

$$V(z(K)) < \alpha^{-2K} V(z(0))$$

Now using formula (7), we get

$$\alpha^K \| z(K) \| < \sqrt{\frac{\beta_2}{\beta_1}} \| z(0) \|$$

So $\lim\limits_{k\to\infty} \alpha^k \| z_k \| = 0$.

We assume that the transmission delays are constant (i. e. $\tau_k = \tau$). This assumption is possible because many static scheduling network protocols, such as token ring and token bus, can provide constant delays. In this case, the rate $r_1 = r_2 = \cdots = r_M = 1/M$, we have the following corollaries.

Corollary 2.2 If there exists a Lyapunov function $V(z) = z^{\mathrm{T}} P z$ and scalars $\alpha_i > 0$ $(i=1,2,\cdots,M)$ corresponding to each state such that

$$\frac{1}{M}(\ln \alpha_1 + \ln \alpha_2 + \cdots + \ln \alpha_M) > 0 \tag{11}$$

$$\Phi_i^{\mathrm{T}} P \Phi_i \leqslant \alpha_i^{-2} P \tag{12}$$

then the NCS model (5) is exponentially stable.

This is a BMI problem in P and $\ln \alpha_i$.

Proof We can get inequality (11) from condition (9) directly.

Condition (8) gives $V(z(t_{k+1})) \leqslant \alpha_i^{-2} V(z(t_k))$.

For $V(z) = z^{\mathrm{T}} P z$, we have $z(t_{k+1})^{\mathrm{T}} P z(t_{k+1}) \leqslant \alpha_i^{-2} z(t_k)^{\mathrm{T}} P z(t_k)$ or $z_{k+1}^{\mathrm{T}} P z_{k+1} \leqslant \alpha_i^{-2} z_k^{\mathrm{T}} P z_k$.

Using model (5), we get

$$z_k^{\mathrm{T}} \Phi_i^{\mathrm{T}} P \Phi_i z_k \leqslant \alpha_i^{-2} z_k^{\mathrm{T}} P z_k$$

So that

$$\Phi_i^{\mathrm{T}} P \Phi_i \leqslant \alpha_i^{-2} P, \ (i = 1,2,\cdots,M).$$

Corollary 2.3 If the controller receives the sensors' data in regular sequence $y_1, y_2, \cdots, y_M$, and $\prod_{i=1}^{M} \Phi_i$ is Schur, the NCS model (5) is exponentially stable.

Proof $z_{kM} = \Phi_M z_{kM-1} = \Phi_M \Phi_{M-1} z_{kM-2} = \cdots = (\prod_{i=M}^{1} \Phi_i) z_{(k-1)M} = (\prod_{i=M}^{1} \Phi_i)^k z_0$. So, if $\prod_{i=M}^{1} \Phi_i$ is Schur, $\prod_{i=1}^{M} \Phi_i$ is Schur and $z_k \to 0$ $(k \to \infty)$.

3 Numerical example

To illustrate the efficiency of the proposed method, we give the following example.

Consider the state-space plant model

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & -0.1 \end{pmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{pmatrix} 0.1 & 0 \\ 0 & 0.1 \end{pmatrix} u(t)$$

$$\begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$$

The controller without networked communication is

$$u(t) = \begin{pmatrix} -3.75 & 0 \\ 0 & -11.5 \end{pmatrix} \begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix}$$

The closed-loop poles are -0.375 and -1.25.

We consider the NCS model of this system. The plant measurement and controller output are both split into two packets. Assuming that the sensor's sampled time h is 0.3 s, and the network delay τ satisfies $0<\tau<2h$, we can achieve the closed-loop NCS model. In this example, $\boldsymbol{F}$, $\boldsymbol{G}$, and $\boldsymbol{H}$ are zero matrices of compatible dimension.

For $M=2$, we have $\boldsymbol{z}_{k+1}=\boldsymbol{\Phi}_i\boldsymbol{z}_k$ ($i=1$, 2), where

$$\boldsymbol{z}_k=\begin{pmatrix}\boldsymbol{x}_k\\ \bar{\boldsymbol{y}}_{k-1}\\ \boldsymbol{u}_{k-1}\\ \boldsymbol{u}_{k-2}\end{pmatrix}=\begin{pmatrix}\boldsymbol{x}_k^1\\ \boldsymbol{x}_k^2\\ \bar{\boldsymbol{y}}_{k-1}^1\\ \bar{\boldsymbol{y}}_{k-1}^2\\ \boldsymbol{u}_{k-1}^1\\ \boldsymbol{u}_{k-1}^2\\ \boldsymbol{u}_{k-2}^1\\ \boldsymbol{u}_{k-2}^2\end{pmatrix}$$

$$\boldsymbol{\Phi}_1=\begin{pmatrix}\Theta+\Gamma_0\boldsymbol{J}P_1\boldsymbol{C} & \Gamma_0\boldsymbol{J}Q_1 & \Gamma_1 & \Gamma_2\\ P_1\boldsymbol{C} & Q_1 & 0 & 0\\ \boldsymbol{J}P_1\boldsymbol{C} & \boldsymbol{J}Q_1 & 0 & 0\\ 0 & 0 & I & 0\end{pmatrix}=$$

$$\begin{pmatrix}0.9625 & 1.3499 & 0 & -0.1208 & 0.0100 & 0.0116 & 0.0100 & 0.0129\\ 0 & 0.9704 & 0 & -0.1150 & 0 & 0.0099 & 0.0100 & 0.0098\\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 1.0000 & 0 & 0 & 0 & 0\\ -3.7500 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -11.50 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 1.0000 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 1.0000 & 0 & 0\end{pmatrix}$$

Similarly, we can get $\boldsymbol{\Phi}_2$.

Now, using corollary 2.2, the problem turns into finding the solution of such BMI

$$0.5(\ln\alpha_1+\ln\alpha_2)>0$$

$$\boldsymbol{\Phi}_i^{\mathrm{T}}\boldsymbol{P}\boldsymbol{\Phi}_i\leqslant\alpha_i^{-2}\boldsymbol{P},\ (i=1,2)$$

By the LMI toolbox of Matlab, we will get an efficient set of α_1, α_2, and $\boldsymbol{P}$.

$$\alpha_1=2.16,\qquad \alpha_2=3.18,$$

$$\boldsymbol{P}=\begin{pmatrix}14.7175 & 0.0697 & -0.0184 & -0.0001 & 0.0027 & 0.0011 & -0.0024 & -0.0017\\ 0.0697 & 13.5254 & -0.0073 & -0.0018 & 0.0009 & 0.0078 & -0.0042 & -0.0021\\ -0.0184 & -0.0073 & 17.0780 & 0 & -0.0002 & -0.0001 & 0.0004 & 0.0002\\ -0.0001 & -0.0018 & 0 & 13.5475 & 0 & 0 & 0 & 0\\ 0.0027 & 0.0009 & -0.0002 & 0 & 12.3305 & 0 & 0 & 0\\ 0.0011 & 0.0078 & -0.0001 & 0 & 0 & 12.5871 & 0 & 0\\ -0.0024 & -0.0042 & 0.0004 & 0 & 0 & 0 & 11.4521 & 0\\ -0.0017 & -0.0021 & 0.0002 & 0 & 0 & 0 & 0 & 11.2379\end{pmatrix}$$

The existence of solution proves the stability of the system. This means that when the plant is sampled every 0.3 s, if the plant outputs are split into two packets and only one packet can be transmitted at a time with a long time delay, we can still guarantee the stability of the feedback control system. Fig. 2 shows that the unit step response of this two-packet transmission setup is similar to the original system.

4 Conclusion

Stability of an NCS with multiple-packet

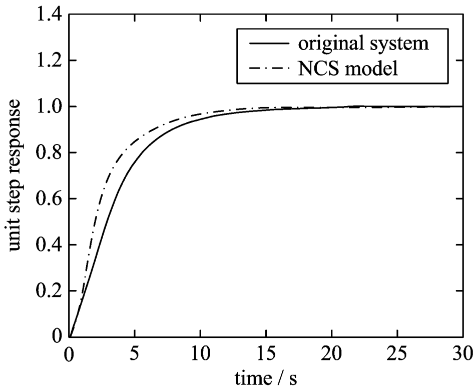

Fig. 2 Comparison of unit step response with original system

transmitted over a limited bandwidth channel was investigated. The communication channel was assumed to permit only one packet transmitted at a time. We discussed this case where the plant measurement was split into different packets and only one packet could be transmitted at a time. Transmission delays were also taken into consideration. We modeled a multiple-packet transmission NCS with long-time network-induced delays in a static pattern as an asynchronous dynamical system. Sufficient conditions on stability of the NCS were obtained. Finally, we gave a simulation example to illustrate the feasibility and efficiency of our approach.

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