Chapter 8

Packet-Based Communication and Control Co-Design for Networked Control Systems

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Abstract A packet-based communication and control co-design framework is proposed for Networked Control Systems (NCSs). This framework takes advantage of the characteristic of the packet-based transmission in the networked control environment, which enables a sequence of control signals to be sent over the network simultaneously within one data packet. This consequently makes it possible to actively compensate for the communication constraints in NCSs with specially designed compensation mechanisms, which can not be achieved by conventional control approaches. These compensated communication constraints include all the major ones brought by the communication network to NCSs, i.e., the network-induced delay, data packet dropout and data packet disorder, thus making the packet-based co-design approach a unified framework for NCSs. Following the design of the packet-based framework, the resulting control system is mathematically formulated, its closed-loop stability is analyzed, and a receding horizon controller is designed to implement the scheme. Finally, the effectiveness of the co-design scheme is verified by numerical examples as well as an Internet-based test rig. It is believed that this packet-based communication and control co-design framework is an important step towards the convergence of control, communication and computation in the new era of the information technology.

8.1 Introduction

Networked control systems (NCSs) are control systems that are closed via communication networks, whose typical structure is depicted in Fig. 8.1. Distinct from conventional control systems where the data exchange between sensors, controllers, actuators, etc., is assumed to be costless, NCSs can contain a large number of control devices interconnected through some form of communication network over

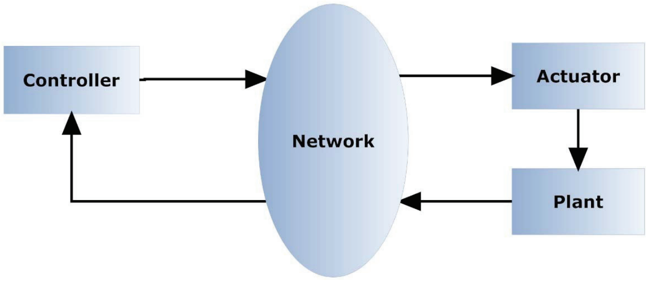

Fig. 8.1 The block diagram of general networked control systems

which data is exchanged. This system structure thus introduces the so-called communication constraints to the control systems, e.g., network-induced delay, data packet dropout, data packet disorder, data rate constraint, etc., making the design and analysis of NCSs a challenging task [Baillieul and Antsaklis (2007); Gupta and Chow (2010); Hespanha *et al.* (2007); Tipsuwan and Chow (2003); Zhang *et al.* (2013)].

As an emerging interdisciplinary research field in recent years, NCSs has attracted much attention from both the communication engineers and the control theory specialists. It has been so widely studied mainly due to its extensive practical applications, existing ones of which include smart home, remote surgery, smart transportation, just name a few, and a lot of potentials are expected in the near future [Hespanha *et al.* (2007)]. These promising applications, generally speaking, benefit from two essential advantages brought by NCSs, that is, the capability of both remote and distributed control. These capabilities are evidently due to the introduction of the communication network to NCSs, thus making the communication network to be essential in NCSs. An increasing trend is also noticed that more and more network-based applications are now configured over the Internet, mainly due to the low cost, easy maintenance, remote control capability, etc., brought by the Internet. However, unlike those conventional control networks such as ControlNet, DeviceNet, etc., that have been specially optimized for control applications [Lian *et al.* (2001)], the Internet is essentially a data network rather than a real-time network, meaning that the Internet is difficult to meet the critical real-time requirement of control systems. This fact implies that worse communication conditions in the Internet such as larger delay, more data packet dropout and disorder, etc., require even more careful treatment before the Internet can be eventually served as a reliable communication media for most control applications [Li *et al.* (2010); Tipsuwan and Chow (2004); Zeng and Chow (2012)].

To date many efforts have been made to deal with these so-called communication constraints in NCSs, ranging from the mathematical modeling and analysis from conventional control theory perspective [Donkers *et al.* (2012); Gao *et al.* (2008); Kruszewski *et al.* (2012); Postoyan and Nesic (2012); Vatanski *et al.* (2009)], to controller design and performance evaluation by taking advantage of the characteristics of the communication network in NCSs [Chen and Qiu (2013); Colandairaj *et al.* (2007); Greco *et al.* (2012); Guan *et al.* (2013); Moayedi *et al.* (2013); Walsh *et al.* (2002); Zhao *et al.* (2009a)], and further to control-oriented communication protocol design from the communication technology perspective [Cea and Goodwin (2013); Katewa and Gupta (2013); Lian *et al.* (2005); Longo *et al.* (2012); Tipsuwan and Chow (2004)], and so forth. Whatever specific methods are used in NCSs, a consensus is always held that the communication constraints are critical in NCSs and a promising approach ought to reduce the negative effects brought by the communication constraints as much as possible. Such approaches can be divided into the following two categories. One is to dynamically schedule the communication resources among different control tasks, in order to make full use of the communication resources efficiently, as done in Walsh and Ye (2001); Zhao *et al.* (2008b). The other way is to reduce the necessary data transmissions while maintaining the system performance at an acceptable level, that is, to find the trade-off between the use of the communication resource and the system performance [Otanez *et al.* (2002); Zhao *et al.* (2011b, 2010b)]. These two means are not fungible but rather, have different focuses. The former is applied to the scenario where the communication network is occupied by multiple NCSs so that the efficient allocation of the communication resources is vital while the latter more focuses on the reduction of the dependence on the communication network for a single NCS.

In this chapter, we exploit the fact that in most communication networks, data is transmitted in "packet" and within its effective load sending a single bit or several hundred bits consumes the same amount of network resources. This makes it possible in NCSs to actively compensate for the communication constraints by sending a sequence of control predictions in one data packet and then selecting the appropriate one corresponding to current network condition. This observation motivates the design of the so called "packet-based control" approach to NCSs in this chapter [Zhao *et al.* (2009a)]. Due to the active compensation process in the packet-based control approach, a better performance can be expected than those from conventional implementations where no characteristics of the network are specifically considered in the design. In a sense this communication and control co-design scheme falls into the first category of the approaches to the efficient usage of the communication resources, i.e., improving the system performance by taking full advantage of the communication networks. On the other hand, the packet-based control approach is flexible to be applied to various system settings, thus making it a unified framework for NCSs. In this chapter we present the approach for the basic system setting. For more applications of the approach, please refer to Zhao *et al.* (2008a,b,c,d,e, 2009b, 2010a, 2011a, 2012a,b,c).

The remainder of the chapter is organized as follows. The characteristic of the packet-based transmission of data in NCSs is first discussed in Section 8.2, to give a general context of the work to be done in this chapter. The packet-based communication and control co-design approach is then presented in detail in Section 8.3, which leads to a novel controller that can compensate for network-induced delay, data packet dropout and data packet disorder simultaneously. The stability criteria for the corresponding closed-loop system are investigated in Section 8.4, from different perspectives of switched system theory and delay-dependent analysis, respectively. The packet-based control framework generally allows any appropriate controller design method to be used, and a Generalized Predictive Control (GPC) based controller is designed in Section 8.5 for an example. Numerical and experimental examples to illustrate the effectiveness of the proposed approach are presented in Section 8.6 and Section 8.7 concludes the chapter.

8.2 Packet-Based Transmission in Networked Control Systems

In conventional control systems data is usually assumed to be transmitted costlessly, while in practical NCSs, the data exchange has to be completed by the communication network, in the form of "data packets". This packet-based transmission is one of the most important characteristics of NCSs that are distinct from conventional control systems [Antsaklis and Baillieul (2007); Baillieul and Antsaklis (2007)]. This characteristic can mean that the perfect data transmission as assumed in conventional control systems is absent in NCSs, thus deriving the most challenging issue in NCSs. The communication constraints caused by the packet-based transmission in NCSs include the network-induced delay, data packet dropout, data packet disorder, etc.. We discuss these in detail as follows.

A. Network-induced delay

With the network being inserted into the control loop in NCSs, network-induced delays are introduced in both the forward and backward channels, which are well known to significantly degrade the performance of the control systems.

Two types of network-induced delays are present according to where they occur.

- τ_{sc}: Network-induced delay from the sensor to the controller, i.e., backward channel delay;
- τ_{ca}: Network-induced delay from the controller to the actuator, i.e., forward channel delay.

The two types of network-induced delays may have different characteristics [Nilsson *et al.* (1998)]. In most cases, however, these delays are not treated separately and only the round trip delay is of interest [Fan *et al.* (2006); Hespanha *et al.* (2007)].

According to the types of the communication networks being used in NCSs, the characteristics of the network-induced delay vary as follows [Lian (2001); Tipsuwan and Chow (2003)].

- Cyclic service networks (e.g., Toking-Ring, Toking-Bus): Bounded delays and can be regarded as constant for certain occasions;
- Random access networks (e.g., Ethernet, CAN): Random and unbounded delays;
- Priority order networks(e.g., DeviceNet): Bounded delays for the data packets with higher priority and unbounded delays for those with lower priority.

Network-induced delay is one of the most important characteristics of NCSs which has been widely addressed in the literature to date, see, e.g., in He (2004); Liu and Shen (2006); Schenato *et al.* (2007); Yue and Han (2005).

B. Data packet dropout

It is well known that the transmission error in communication networks is inevitable, which in the case of NCSs then produces a situation called "data packet dropout". Data packet dropout can occur either in the backward or forward channel, and it makes either the sensing data or the control signals unavailable to NCSs, thus significantly degrading the performance of NCSs.

In communication networks, two different strategies are applied when a data packet is lost, that is, either to send the packet again or simply discard it. Using the terms from communication networks, these two strategies are called Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) respectively [Stallings (2000)]. It is readily seen that with TCP, all the data packets will be received successfully, although it may take a considerably long time for some data packets; while with UDP, some data packets will be lost forever.

As far as NCSs is concerned, UDP is used in most applications due to the real-time requirement and the robustness of control systems. As a result, the effect of data packet dropout in NCSs has to be explicitly considered, as done in, e.g., Azimi-Sadjadi (2003); Imer *et al.* (2006); Xiong and Lam (2007) and the packet-based control approach in this chapter.

C. Data packet disorder

In most communication networks, different data packets suffer different delays, as mentioned above; it therefore produces a situation where a data packet sent earlier may arrive at the destination later or vice versa, that is, data packet disorder. This characteristic in NCSs can mean that a newly arrived control signal in NCSs may not be the latest, which never occurs in conventional control systems. Therefore, the effect of data packet disorder has to be specially dealt with. This, however, has rarely been touched to date. We will show later that this effect can be effectively overcome by using the comparison process in the packet-based control approach.

8.3 Packet-Based Control for Networked Control Systems

The NCS setup considered in this chapter is shown in Fig. 8.2, where $\tau_{sc,k}$ and $\tau_{ca,k}$ are the backward and forward channel delays, respectively. The plant is linear in discrete-time, represented by

$$\begin{aligned} \mathcal{S}_d\colon x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned} \tag{8.1}$$

with the system states $x(k) \in \mathbb{R}^n$, the control signals $u(k) \in \mathbb{R}^m$, and the system matrices $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$ and $C \in \mathbb{R}^{r\times n}$.

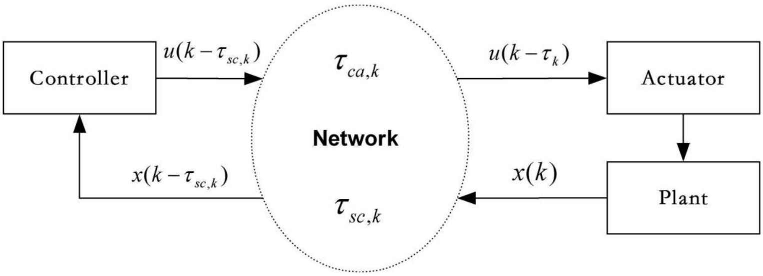

Fig. 8.2 The block diagram of networked control systems in discrete time

8.3.1 *Packet-based control for NCSs: A unified model*

For the system in (8.1), the conventional state feedback law is usually obtained as follows without considering the communication constraints in NCSs,

$$u(k) = Kx(k) \tag{8.2}$$

where the feedback gain K is time-invariant.

However, when the network-induced delay is considered, the state feedback law can not be simply defined as in (8.2) due to the unavailability of the current state information. The resulting control law using conventional approaches in time delay systems theory would have the following form

$$u(k) = Kx(k-\tau_k) \tag{8.3}$$

where the effect of the delay is not been specially treated in the design. Furthermore, when data packet dropout is also present, it can be seen from Fig. 8.2 that no matter where data packet dropout occurs, a certain control input will be unavailable to the actuator. In conventional time delay systems theory, there are mainly two ways to deal with this situation, either use the previous control input or adopt zero control [Richard (2003)]. For example, in Wu and Chen (2007), the last step of the control signal is used in the case of an unsuccessful transmission, as follows,

$$u(k) = \begin{cases} \bar{u}(k) & \text{if transmitted successfully,} \\ u(k-1) & \text{otherwise,} \end{cases} \tag{8.4}$$

where $\bar{u}(k)$ is the newly arrived control signal at time k.

Although the conventional control strategies in (8.3) and (8.4) are simple to implement, they are conservative in that they overlook the potential of providing an active prediction for the unavailable control input using available information of the system dynamics and previous system trajectory.

On the contrary, the control law based on the packet-based control approach is obtained as follows with explicit compensation for the communication constraint (see Algorithm 8.1 to be given later)

$$u(k) = K(\tau^*_{sc,k}, \tau^*_{ca,k})x(k - \tau^*_{sc,k} - \tau^*_{ca,k}), \tag{8.5}$$

or simply (see Algorithm 8.2 which will be given later)

$$u(k) = K(\tau^*_k)x(k - \tau^*_k) \tag{8.6}$$

where $\tau^*_{sc,k}$ and $\tau^*_{ca,k}$ are the network-induced delays of the control action that is actually applied to the plant at time k and $\tau^*_k = \tau^*_{sc,k} + \tau^*_{ca,k}$.

It is seen from the control laws in (8.5) and (8.6) that in the packet-based control approach, different feedback gains apply for different network conditions. This is why we call it a "Varying Feedback Gain" (VFG) scheme for NCSs. As will be presented later, these packet-based control laws can actively deal with the network-induced delay, data packet dropout and data packet disorder simultaneously, and therefore can be regarded as a unified model for NCSs. This control strategy can be compared with the conventional approach as in (8.3) and (8.4) where no active compensation is available.

Remark 8.1. In Zhang *et al.* (2005), the authors noticed the unavailability of the forward channel delay $\tau_{ca,k}$ and a controller was designed with the following form

$$u(k) = K(\tau_{sc,k}, \tau_{ca,k-1})x(k - \tau_{sc,k} - \tau_{ca,k}) \tag{8.7}$$

where the forward channel delay of the last step $\tau_{ca,k-1}$ was used instead. However, actually even $\tau_{ca,k-1}$ is generally unavailable for the controller in NCSs since in the case of a arbitrary forward channel delay, $\tau_{ca,k-1}$ can not be known to the controller until the controller receives information of $\tau_{ca,k-1}$ from the actuator. Therefore, it is seen that $\tau_{ca,k-1}$ can not be available for the controller earlier than time $k - 1 + \tau_{ca,k-1}$ even if an additional delay-free channel exists to send the information of $\tau_{ca,k-1}$ from the actuator to the controller. As a result, the above model in (8.7) is inappropriate in practice unless a special control structure is designed for the networked control environment as done in this chapter.

8.3.2 *Design of the packet-based control scheme*

For the design of the packet-based control scheme, the following assumptions are required.

Assumption 8.1. The control components in the considered NCS including the sensor, the controller and the actuator, are time-synchronized and the data packets sent from both the sensor and the controller are time-stamped.

Assumption 8.2. The sum of the maximum forward (backward) channel delay and the maximum number of continuous data packet dropout is upper bounded by $\bar{\tau}_{ca}$ ($\bar{\tau}_{sc}$ accordingly) and

$$\bar{\tau}_{ca} \leq \frac{B_p}{B_c} - 1 \tag{8.8}$$

where B_p is the size of the effective load of the data packet and B_c is the bits required to encode a single step control signal.

Remark 8.2. From Assumption 8.1, the network-induced delay that each data packet experiences is known by the controller and the actuator on its arrival.

Remark 8.3. Assumption 8.2 is required due to the need of packing the forward control signals and compensating for the network-induced delay in the packet-based control approach, which will be detailed later. The constraint in (8.8) is easy to be satisfied, e.g., $B_p = 368$bit for an Ethernet IEEE 802.3 frame which is often used [Stallings (2000)], while an 8-bit data (i.e., $B_c = 8$bit) can encode $2^8 = 256$ different control actions which is ample for most control implementations; In this case, 45 steps of forward channel delay is allowed by (8.8) which can actually meet the requirements of most practical control systems.

The block diagram of the packet-based control structure is illustrated in Fig. 8.3. It is distinct from a conventional control structure in two aspects: the specially designed packet-based controller and the corresponding Control Action Selector (CAS) at the actuator side.

In order to implement the control law in (8.5) and (8.6), we take advantage of the packet-based transmission of the network to design a packet-based controller

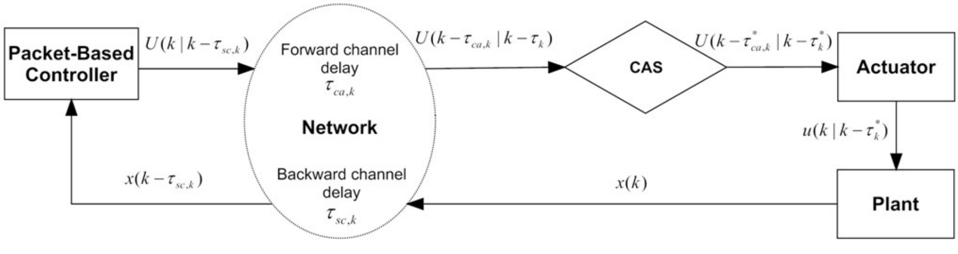

Fig. 8.3 Packet-based networked control systems in discrete time (with time synchronization)

instead of trying to obtain directly the current forward channel delay as this is actually impossible in practice. As for the control law in (8.5), the packet-based controller determines a sequence of forward control actions (called "Forward Control Sequence" (FCS)) as follows and sends them together in one data packet to the actuator,

$$U_1(k|k-\tau_{sc,k}) = [u(k|k-\tau_{sc,k}) \ \ldots \ u(k+\bar{\tau}_{ca}|k-\tau_{sc,k}]^{\mathsf{T}} \tag{8.9}$$

where $u(k+i|k-\tau_{sc,k}), i = 0, 1, \ldots, \tau_{ca,k}$ are the forward control action predictions based on information up to time $k - \tau_{sc,k}$.

When a data packet arrives at the actuator, the designed CAS compares its time stamp with the one already in CAS and only the one with the latest time stamp is saved. Denote the forward control sequence already in CAS and the one just arrived by $U_1(k_1 - \tau_{ca,k_1}|k_1 - \tau_{k_1})$ and $U_1(k_2 - \tau_{ca,k_2}|k_2 - \tau_{k_2})$ respectively, then the chosen sequence is determined by the following comparison rule

$$U_1(k-\tau^*_{ca,k}|k-\tau^*_k) = \begin{cases} U_1(k_2 - \tau_{ca,k_2}|k_2 - \tau_{k_2}), \text{ if } k_1 - \tau_{k_1} < k_2 - \tau_{k_2}; \\ U_1(k_1 - \tau_{ca,k_1}|k_1 - \tau_{k_1}), \text{ otherwise.} \end{cases} \tag{8.10}$$

The comparison process is introduced to deal with data packet disorder. After the comparison process, only the latest available information is used and the effect of data packet disorder is effectively overcome.

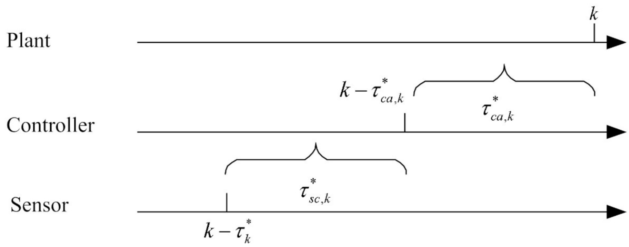

Fig. 8.4 Timeline in packet-based networked control systems

CAS also determines the appropriate control action from the FCS $U_1(k-\tau^*_{ca,k}|k-\tau^*_k)$ at each time instant as follows

$$u(k) = u(k|k-\tau^*_k). \tag{8.11}$$

The timeline of the packet-based control approach is illustrated in Fig. 8.4. It is necessary to point out that the appropriate control action determined by (8.11) is always available provided Assumption 8.2 holds.

The packet-based control algorithm under Assumptions 8.1 and 8.2 can now be summarized as follows.

In practice, it is often the case that we do not need to identify separately the forward and backward channel delays since it is normally the round trip delay that affects the system performance. In such a case, the simpler control law in (8.6)

Algorithm 8.1 Packet-based control with the control law in (8.5)

1: At time k, if the packet-based controller receives the delayed state data $x(k-\tau_{sc,k})$, it then:
(1a) Reads the current backward channel delay $\tau_{sc,k}$;
(1b) Calculates the FCS as in (8.9);
(1c) Packs $U_1(k|k-\tau_{sc,k})$ and sends it to the actuator in one data packet with time stamps k and $\tau_{sc,k}$.
If no data packet is received at time k, then let $k=k+1$ and wait for the next time instant.
2: CAS updates its FCS by (8.10) once a data packet arrives;
3: The control action in (8.11) is picked out from CAS and applied to the plant.

instead of that in (8.5) is applied, for which the following assumption is required instead of Assumption 8.2.

Assumption 8.3. The sum of the maximum network-induced delay and the maximum number of continuous data packet dropout in round trip is upper bounded by $\bar{\tau}$ and

$$\bar{\tau} \leq \frac{B_p}{B_c} - 1. \tag{8.12}$$

With the above assumption, the packet-based controller is modified as follows

$$U_2(k-\tau_{sc,k}|k-\tau_{sc,k}) = [u(k-\tau_{sc,k}|k-\tau_{sc,k}) \ \ldots \ u(k-\tau_{sc,k}+\bar{\tau}|k-\tau_{sc,k}]^{\mathsf{T}}. \tag{8.13}$$

It is noticed that in such a case the backward channel delay $\tau_{sc,k}$ is not required for the controller, since the controller simply produces $(\bar{\tau}+1)$ step forward control actions whenever a data packet containing sensing data arrives. This relaxation implies that the time-synchronization between the controller and the actuator (plant) is not required any more and thus Assumption 8.1 can then be modified as follows.

Assumption 8.4. The data packets sent from the sensor are time-stamped.

The comparison rule in (8.10) and the determination of the actual control action in (8.11) remain unchanged since both of them are based on the round trip delay τ_k. The packet-based control algorithm with the control law in (8.6) can now be summarized as follows based on Assumptions 8.3 and 8.4.

The block diagram of the packet-based control approach in Algorithm 8.2 is illustrated in Fig. 8.5.

8.4 Stability of Packet-Based Networked Control Systems

In this section the stability criteria for the system in (8.1) using the aforementioned packet-based control approach with the control laws in (8.5) and (8.6) are investi-

Algorithm 8.2 Packet-based control with the control law in (8.6)

1: At time k, if the packet-based controller receives the delayed state data $x(k - \tau_{sc,k})$, then,
(1a) Calculate the FCS as in (8.13);
(1b) Pack $U_2(k - \tau_{sc,k}|k - \tau_{sc,k})$ and send it to the actuator in one data packet.
If no data packet is received at time k, then let $k = k + 1$ and wait for the next time instant.

2: Steps 2 and 3 remain the same as in Algorithm 8.1.

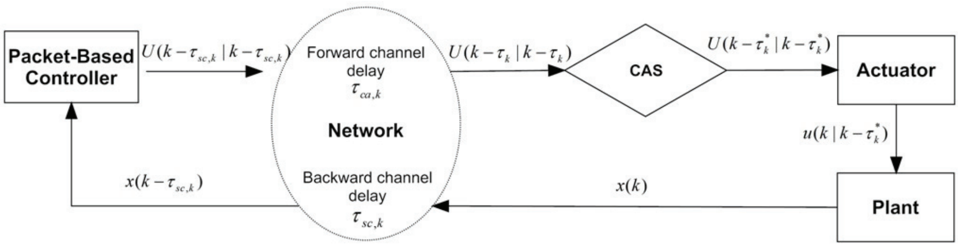

Fig. 8.5 Packet-based networked control systems in discrete time (without time synchronization)

gated. Two stability analysis approaches, i.e., results from switched system theory and delay-dependent analysis, are applied, by modeling the closed-loop system into different forms. Unless otherwise specified, all the stability related notions in this chapter are under the Lyapunov stability framework.

8.4.1 *A switched system theory approach*

An intuitive observation on the packet-based control approach is that, at every execution time, a specific control action is determined by the CAS according to the current network condition. Thus, regarding this selection process as "switches" among different subsystems, then yields the following analysis from the viewpoint of switched system theory.

Let $X(k) = [x(k) \; x(k-1) \; \cdots \; x(k-\bar{\tau})]$. The closed-loop formula for the system in (8.1) using the packet-based controllers in (8.5) and (8.6) can then be represented in augmented forms as

$$X(k+1) = \Xi_{\tau^*_{sc,k}, \tau^*_{ca,k}} X(k) \tag{8.14}$$

and

$$X(k+1) = \Xi_{\tau^*_k} X(k) \tag{8.15}$$

respectively, where

$$\Xi_{\tau^*_{sc,k},\tau^*_{ca,k}} = \begin{pmatrix} A & \cdots & BK_{\tau^*_{sc,k},\tau^*_{ca,k}} & \cdots & \cdots \\ I_n & & & & 0 \\ & I_n & & & 0 \\ & & \ddots & & \vdots \\ & & & I_n & 0 \end{pmatrix}$$

$$\Xi_{\tau^*_k} = \begin{pmatrix} A & \cdots & BK_{\tau^*_k} & \cdots & \cdots \\ I_n & & & & 0 \\ & I_n & & & 0 \\ & & \ddots & & \vdots \\ & & & I_n & 0 \end{pmatrix}$$

and I_n is the identity matrix with rank n.

With the closed-loop system model in (8.14), we then obtain the following stability criterion.

Theorem 8.1. *The closed-loop system in (8.14) is stable if there exists a positive definite solution* $P = P^{\mathsf{T}} > 0$ *for the following* $(\bar{\tau}_{sc} + 1) \times (\bar{\tau}_{ca} + 1)$ *LMIs*

$$\Xi^{\mathsf{T}}_{\tau^*_{sc,k},\tau^*_{ca,k}} P \Xi_{\tau^*_{sc,k},\tau^*_{ca,k}} - P < 0.$$

Proof. Let $V(k) = X^{\mathsf{T}}(k)PX(k)$ be a Lyapunov candidate, and then its increment along the system in (8.14) can be obtained as

$$\begin{aligned} \Delta V(k) &= V(k+1) - V(k) \\ &= X^{\mathsf{T}}(k)(\Xi^{\mathsf{T}}_{\tau^*_{sc,k},\tau^*_{ca,k}} P \Xi_{\tau^*_{sc,k},\tau^*_{ca,k}} - P)X(k) \\ &< 0 \end{aligned}$$

which completes the proof. □

The following stability criterion for the closed-loop system model in (8.15) readily follows from Theorem 8.1.

Proposition 8.1. *The closed-loop system in (8.15) is stable if there exists a positive definite solution* $P = P^{\mathsf{T}} > 0$ *for the following* $(\bar{\tau} + 1)$ *LMIs*

$$\Xi^{\mathsf{T}}_{\tau^*_k} P \Xi_{\tau^*_k} - P < 0.$$

8.4.2 *A delay dependent analysis approach*

In this subsection, the closed-loop stability is investigated using a delay dependent analysis approach as in He (2004).

Without augmenting the system states as done in the last subsection, the closed-loop formula for the system in (8.1) using the packet-based controller in (8.5) can be obtained as

$$x(k+1) = Ax(k) + BK(\tau^*_{ca,k}, \tau^*_{sc,k})x(k - \tau^*_k). \tag{8.16}$$

It is noticed that in practice there is at least a single step delay in both the forward and backward channels, and therefore we have $\tau^*_k = \tau^*_{sc,k} + \tau^*_{ca,k} \geq 2$. Let $\bar{K} = \max_{2 \leq \tau^*_k \leq \bar{\tau}_{ca} + \bar{\tau}_{sc}} ||K(\tau^*_{ca,k}, \tau^*_{sc,k})||$ where $||\cdot||$ denotes the Euclidean norm. Then $BK(\tau^*_{ca,k}, \tau^*_{sc,k})$ can be represented by

$$BK(\tau^*_{ca,k}, \tau^*_{sc,k}) = B_m \cdot K'(\tau^*_{ca,k}, \tau^*_{sc,k}) \tag{8.17}$$

where $B_m = \bar{K}B$ is a constant matrix and $K'(\tau^*_{ca,k}, \tau^*_{sc,k}) = \frac{K(\tau^*_{ca,k}, \tau^*_{sc,k})}{\bar{K}}$. It is readily to conclude that $||K'(\tau^*_{ca,k}, \tau^*_{sc,k})|| \leq 1, \ \forall\ 1 \leq \tau^*_{ca,k} \leq \bar{\tau}_{ca}, 1 \leq \tau^*_{sc,k} \leq \bar{\tau}_{sc}$.

Theorem 8.2. *If there exists* $P_i = P_i^{\mathsf{T}} > 0, \ i = 1, 2, 3, \ X = \begin{pmatrix} X_{11} & X_{12} \\ * & X_{22} \end{pmatrix} \geq 0$, $N_i, i = 1, 2$ *with appropriate dimensions and* $\gamma > 0$ *satisfying the following two LMIs,*

$$\begin{pmatrix} X_{11} & X_{12} & N_1 \\ * & X_{22} & N_2 \\ * & * & P_3 \end{pmatrix} \geq 0 \tag{8.18}$$

$$\begin{pmatrix} \Phi_{11} & \Phi_{12} & (A-I)^{\mathsf{T}}H & P_1 B_m \\ * & \Phi_{22} + \gamma I & 0 & 0 \\ * & * & -H & HB_m \\ * & * & * & -\gamma I \end{pmatrix} < 0 \tag{8.19}$$

where

$$\begin{aligned} \Phi_{11} &= (\bar{\tau} - 1)P_2 + P_1(A - I) + (A - I)^{\mathsf{T}} P_1 \\ &\quad + N_1 + N_1^{\mathsf{T}} + \bar{\tau} X_{11}, \\ \Phi_{12} &= N_2^{\mathsf{T}} - N_1 + \bar{\tau} X_{12}, \\ \Phi_{22} &= -P_2 - N_2 - N_2^{\mathsf{T}} + \bar{\tau} X_{22}, \\ H &= P_1 + \bar{\tau} P_3, \end{aligned}$$

then the closed-loop system in (8.16) is stable.

Proof. Let $d_1 = 2$, $d_2 = \bar{\tau}$, and $\Delta A_d(k) = BK(\tau^*_{ca,k}, \tau^*_{sc,k})$ in Theorem 7.3 in He (2004), then the above theorem can be obtained using the same techniques as in He (2004). □

Remark 8.4. Following the same procedure, the stability criterion for the system in (8.1) using the packet-based controller in (8.6) can be obtained analogously.

Remark 8.5. It is seen that the aforementioned stability criteria are simple propositions of existing results from switched system theory and delay-dependent analysis respectively. The former emphasizes on the "switch" property of packet-based control while the latter on the "time delay" property of the system. However, none of them is perfect: the switched system theory approach does not consider explicitly the time delay by augmenting the system states, whilst the delay-dependent analysis approach neglects the "switch" property which therefore leads to a stability criterion that is valid for any type of delay changes within an allowed upper bound. Hence, better stability analysis is still needed for the proposed packet-based control approach.

Up to now we have provided the packet-based control structure for NCSs whilst the controller design remains open. Indeed, under the packet-based control framework, any controller design approach can be used to obtain the VFGs as in (8.5) and (8.6) provided it can result in a satisfactory system performance. In the following section, a GPC-based controller is designed as an example.

8.5 Packet-Based Controller Design: A GPC-Based Approach

In GPC, an optimization process is repeated at every control instant to determine a sequence of forward control signals that optimize future open-loop plant behavior based on current system information. Different from conventional GPC implementations where only the first control prediction is actually applied to the plant, in this chapter the first $\bar{\tau}_{ca}+1$ (or $\bar{\tau}+1$ for the control law in (8.6)) forward control predictions are all used to implement the packt-based control approach proposed in the previous section.

Taking account of the communication constraints in NCSs which delay the sensing data, the objective function for open-loop optimization in GPC is therefore defined as follows,

$$J_{k,\tau_{sc,k}} = X^{\mathsf{T}}(k|k-\tau_{sc,k})QX(k|k-\tau_{sc,k}) + U'^{\mathsf{T}}(k|k-\tau_{sc,k})RU'(k|k-\tau_{sc,k}) \quad (8.20)$$

where $J_{k,\tau_{sc,k}}$ is the objective function at time k, $U'(k|k-\tau_{sc,k}) = [u(k-\tau_{sc,k}|k-\tau_{sc,k})\cdots u(k+N_u-1|k-\tau_{sc,k})]^{\mathsf{T}}$ is the FCS, $X(k|k-\tau_{sc,k}) = [x(k+1|k-\tau_{sc,k})\cdots x(k+N_p|k-\tau_{sc,k})]^{\mathsf{T}}$ is the predictive state trajectory, Q and R are constant weighting matrixes and N_p and N_u are the prediction horizon and the control horizon respectively.

The predictive states at time k based on the state at time $k-\tau_{sc,k}$ and the control sequences from $k-\tau_{sc,k}$ can be obtained by iteration as

$$x(k+j|k-\tau_{sc,k}) = A^{j+\tau_{sc,k}}x(k-\tau_{sc,k}) + \sum_{l=-\tau_{sc,k}}^{j-1} A^{j-l-1}Bu(k+l|k-\tau_{sc,k}), j=1,2,\cdots,N_p.$$

Thus, we obtain

$$X(k|k-\tau_{sc,k}) = E_{\tau_{sc,k}}x(k-\tau_{sc,k}) + F_{\tau_{sc,k}}U'(k|k-\tau_{sc,k})$$

where $E_{\tau_{sc,k}} = [(A^{\tau_{sc,k}+1})^{\mathsf{T}} \cdots (A^{\tau_{sc,k}+N_p})^{\mathsf{T}}]^{\mathsf{T}}$ and $F_{\tau_{sc,k}}$ is a block lower triangular matrix with its non-null blocks defined by $(F_{\tau_{sc,k}})_{ij} = A^{\tau_{sc,k}+i-j}B$, $j - i \leq \tau_{sc,k}$.

The optimal control inputs can then be calculated by substituting the above equation to (8.20) and optimizing $J_{k,\tau_{sc,k}}$, which turns out to be state feedback control,

$$u(k+j|k-\tau_{sc,k}) = K_{\tau_{sc,k},j}x(k-\tau_{sc,k}), \quad j = 0, 1, 2, \ldots, \bar{\tau}_{ca}$$

where $K_{\tau_{sc,k}} = [K^{\mathsf{T}}_{\tau_{sc,k},0} \cdots K^{\mathsf{T}}_{\tau_{sc,k},\bar{\tau}_{ca}}]^{\mathsf{T}}$, can be calculated by

$$K_{\tau_{sc,k}} = -M_{\tau_{sc,k}}(F^{\mathsf{T}}_{\tau_{sc,k}}QF_{\tau_{sc,k}} + R)^{-1}F^{\mathsf{T}}_{\tau_{sc,k}}QE_{\tau_{sc,k}}$$

and $M_{\tau_{sc,k}} = [0_{m(\bar{\tau}_{ca}+1)\times m\tau_{sc,k}} \; I_{m(\bar{\tau}_{ca}+1)\times m(\bar{\tau}_{ca}+1)} \; 0_{m(\bar{\tau}_{ca}+1)\times m(N_u-\bar{\tau}_{ca})}]$. The FCS in (8.9) for Algorithm 8.1 can then be constructed by

$$U(k|k-\tau_{sc,k}) = K_{\tau_{sc,k}}x(k-\tau_{sc,k}). \tag{8.21}$$

The FCS in (8.13) for Algorithm 8.2 can also be constructed analogously.

Remark 8.6 (State observer). *If the state vector x is not available, an observer must be included*

$$\hat{x}(k+1|k) = A\hat{x}(k|k-1) + Bu(k) + L(y_m(k) - C\hat{x}(k|k-1)) \tag{8.22}$$

where $\hat{x}(k)$ is the observed state at time k, and $y_m(k)$ is the measured output. If the plant is subject to white noise disturbances affecting the process and the output with known covariance matrices, the observer becomes a Kalman filter and the gain L is calculated solving a Riccati equation.

Remark 8.7. In Liu *et al.* (2007), state feedback $u_k = K\hat{x}_{k|k-\tau_{sc,k}}$ was also used, where K was artificially chosen without consideration of the communication constraints and $\hat{x}_{k|k-\tau_{sc,k}}$ depends on "the state estimation $\hat{x}_{k-\tau_{sc,k}|k-\tau_{sc,k}-1}$, the past control input up to u_{k-1}, and the past output up to $y_{k-\tau_{sc,k}}$ of the system". However, under the compensation scheme in the forward channel in Liu *et al.* (2007), the whole sequence of the optimal forward control signals $U(k|k-\tau^*_{sc,k})$ is sent to the actuator and only one of them is chosen to be applied to the plant. Thus, unless information from the actuator is received we have no idea which control prediction was really used if the data packets in the forward channel were arbitrarily delayed. Hence, the use of the previous control inputs implies an additional communication channel which can send the applied control inputs to the controller efficiently. Without such a channel, the approaches proposed in these publications are only applicable to such a situation where there is no delay or data packet dropout in the forward channel. This requirement is relaxed in this section by redesigning the controller where the objective function includes as part of it the previous control increment sequence from $k - \tau_{sc,k}$ to $k-1$. As a result, the FCS at time k are only based on data up to time $k - \tau_{sc,k}$, which is always available in practice.

8.6 Numerical and Experimental Examples

In this section, numerical and experimental examples are presented to illustrate the effectiveness of the proposed packet-based control approach to NCSs.

8.6.1 *Numerical examples*

Example 8.1 (Validating the GPC-based controller). A second order system in (8.1) is adopted, which is open-loop unstable with the following system matrices,

$$A = \begin{pmatrix} 0.98 & 0.1 \\ 0 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} 0.04 \\ 0.1 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

In order to illustrate the effectiveness of the proposed packet-based control approach compared with conventional design approach, the Linear Quadratic Optimal (LQR) control method is used to design a state feedback law for this system without consideration of the communication constraints, which yields the time-invariant feedback gain $K_{LQR} = [0.7044\ 1.3611]$. In the simulation, the initial state $x_0 = [-1\ -1]^{\mathsf{T}}$, the upper bounds of the delays and continuous dropout (disorder) are $\bar{\tau} = 3, \bar{\tau}_{ca} = 2, \bar{\tau}_{sc} = 1$, and the control and prediction horizon in the GPC-based controller proposed in Section 8.5 are set as $N_u = 8, N_p = 10$ respectively. The delays in both channels are set to vary arbitrarily within their upper bounds.

The simulation results show that it is unstable using this LQR controller (Fig. 8.6) while it is stable using the packet-based control approach (Fig. 8.7) in the presence of communication constraints.

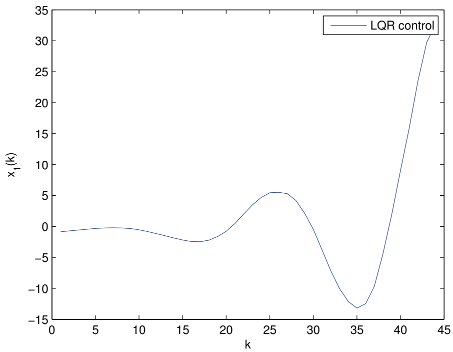

Fig. 8.6 System is unstable using LQR controller in Example 8.1

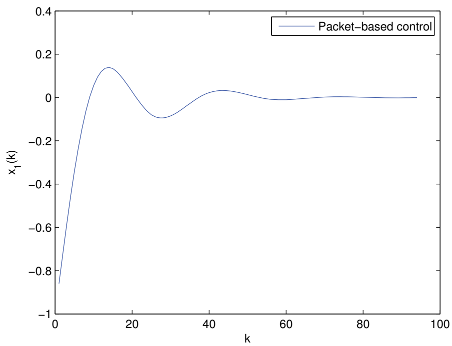

Fig. 8.7 System is stable using packet-based controller in Example 8.1

Example 8.2 (Example 1 in Liu *et al.* (2007)). The system matrices for the system in (8.1) are as follows,

$$A = \begin{pmatrix} 1.0100 & 0.2710 & -0.4880 \\ 0.4820 & 0.1000 & 0.2400 \\ 0.0020 & 0.3681 & 0.7070 \end{pmatrix}, \quad B = \begin{pmatrix} 5 & 5 \\ 3 & -2 \\ 5 & 4 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 3 & 1 \end{pmatrix}.$$

In Liu *et al.* (2007), the above system is illustrated to be stable with the observer in (8.22) where $\bar{\tau}_{sc} = 2$, $\bar{\tau}_{ca} = 1$, and

$$L = \begin{pmatrix} -0.3614 & 0.3326 \\ 0.0332 & 0.0576 \\ 0.2481 & -0.0750 \end{pmatrix}, \quad K = \begin{pmatrix} 0.5858 & -0.1347 & -0.4543 \\ -0.5550 & 0.0461 & 0.4721 \end{pmatrix}.$$

However, using the packet-based control approach, this system is unstable with the same $\bar{\tau}_{sc}$, $\bar{\tau}_{ca}$ and L (see Fig. 8.8. Other parameters: $N_u = 8$, $N_p = 10$.). This fact seems to mean the approach in Liu *et al.* (2007) is better than the approach in this chapter, but we need to remember that the approach in Liu *et al.* (2007) takes advantage of more information to design the predictive controller and some of the information used is not easy to obtain in practice (Remark 8.7). On the other hand, the simulation results do illustrate that the VFG scheme in this chapter is superior to the previous Fixed Feedback Gain (FFG) scheme in Liu *et al.* (2007), where the same system is stable using the approach in this chapter when $\bar{\tau}_{sc} = \bar{\tau}_{sc} = 1$ (Fig. 8.9) and yet is unstable using the same state feedback in (8.16) with the fixed K above (Fig. 8.10).

Example 8.3 (Validating Theorem 8.2). The system matrices for the system in (8.1) are set as

$$A = \begin{pmatrix} 0.7 & 0.2 \\ 0.3 & 0.5 \end{pmatrix}, \quad B = \begin{pmatrix} 0.05 \\ 0.2 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & 0 \end{pmatrix}.$$

This system can be shown using Theorem 8.2 to be stable under $\bar{\tau}_{sc} = 3$, $\bar{\tau}_{ca} = 2$, $N_u = 8$, $N_p = 10$. The simulation result is illustrated in Fig. 8.11.

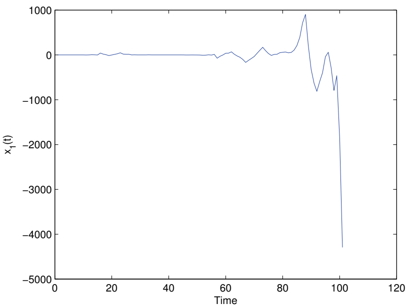

Fig. 8.8 Example 8.2. Packet-based control, unstable, $\bar{\tau}_{sc} = 2$, $\bar{\tau}_{ca} = 1$

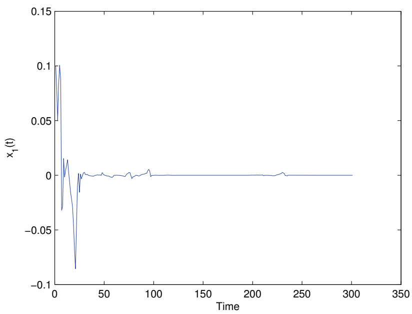

Fig. 8.9 Example 8.2. VFG scheme, stable, $\bar{\tau}_{sc} = 1$, $\bar{\tau}_{ca} = 1$

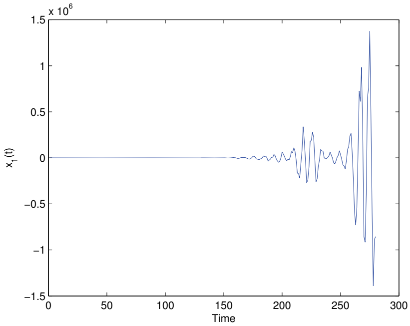

Fig. 8.10 Example 8.2. FFG scheme, unstable, $\bar{\tau}_{sc} = 1$, $\bar{\tau}_{ca} = 1$

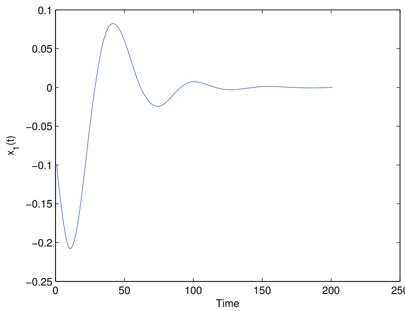

Fig. 8.11 Example 8.3. Packet-based control, stable, $\bar{\tau}_{sc} = 3$, $\bar{\tau}_{ca} = 2$

8.6.2 *Experimental example*

Example 8.4 (Experimental example). In this example, an Internet-based test rig is used to verify the effectiveness of the packet-based control approach. This test rig consists of a plant (DC servo system, see Fig. 8.12) which is located in the University of Glamorgan, Pontypridd, UK, and a remote controller which is located in the Institute of Automation, Chinese Academy of Sciences, Beijing, China (see Fig. 8.13). The plant and the controller are connected via the Internet. A web-based laboratory is also available at *www.ncslab.net* to implement experiments online. For further information of this test rig, the reader is referred to Hu (2008); Hu *et al.* (2007).

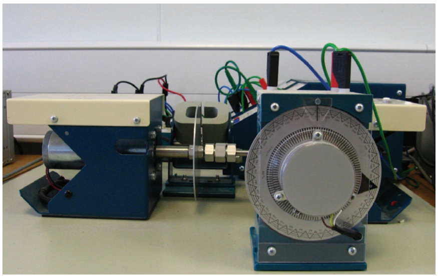

Fig. 8.12 The DC servo plant at the University of Glamorgan

Fig. 8.13 The network controller at the Chinese Academy of Sciences

The DC servo system is identified by Hu (2008) to be a third-order system and in state-space description has the following system matrices:

$$A = \begin{pmatrix} 1.12 & 0.213 & -0.333 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad C = \begin{pmatrix} 0.0541 & 0.0050 & 0.0001 \end{pmatrix}.$$

To enable the use of state feedback in the packet-based control approach, a state observer as in Remark 8.6 is designed with $L = [6\ 6\ 6]^{\mathsf{T}}$. The packet-based controller is calculated by using the GPC-based controller design approach in Section 8.5. To this end, the upper bounds of the network-induced delays (data packet dropout as well) in both forward and backward channels are assumed to be 4 steps of the sampling period (The sampling period is set as 0.04s and thus the delay bounds are 0.16s for both backward and forward channel delays.), since typically the round trip delay in the experiment is not larger than 0.32s. The packet-based controller can then be obtained as:

$$K = [K_0^{\mathsf{T}}\ \ K_1^{\mathsf{T}}\ \ K_2^{\mathsf{T}}\ \ K_3^{\mathsf{T}}\ \ K_4^{\mathsf{T}}]^{\mathsf{T}}, \quad K_0 = \begin{pmatrix} -1.3217 & 0.1276 & 0.4296 \\ -0.1356 & 0.0306 & 0.0445 \\ 0.2688 & -0.0220 & -0.0816 \\ 0.1255 & -0.0096 & -0.0396 \\ 0.0610 & -0.0061 & -0.0190 \end{pmatrix},$$

$$K_1 = \begin{pmatrix} -0.2193 & 0.0219 & 0.0844 \\ 0.2177 & -0.0032 & -0.0662 \\ 0.1298 & -0.0087 & -0.0381 \\ 0.0621 & -0.0035 & -0.0198 \\ 0.0114 & -0.0014 & -0.0035 \end{pmatrix}, \quad K_2 = \begin{pmatrix} 0.1120 & 0.0005 & -0.0201 \\ 0.1183 & 0.0032 & -0.0348 \\ 0.0726 & -0.0050 & -0.0201 \\ 0.0192 & -0.0007 & -0.0062 \\ 0.0035 & -0.0009 & -0.0010 \end{pmatrix},$$

$$K_3 = \begin{pmatrix} 0.0894 & 0.0021 & -0.0130 \\ 0.0832 & 0.0056 & -0.0239 \\ 0.0398 & -0.0028 & -0.0099 \\ 0.0106 & -0.0001 & -0.0035 \\ 0.0007 & -0.0007 & -0.0002 \end{pmatrix}, \quad K_4 = \begin{pmatrix} 0.0721 & 0.0030 & -0.0076 \\ 0.0515 & 0.0073 & -0.0140 \\ 0.0267 & -0.0021 & -0.0058 \\ 0.0059 & 0.0001 & -0.0021 \\ 0.0005 & -0.0007 & -0.0001 \end{pmatrix},$$

where the subscripts of K_0, K_1, K_2, K_3 and K_4 are with respect to different backward channel delays.

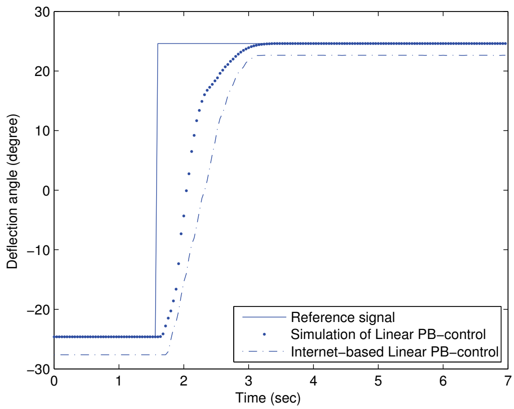

Fig. 8.14 Comparison between simulation and experimental results of linear packet-based control system in Example 8.4

The comparison between the simulation and experimental results is illustrated in Fig. 8.14, which shows that the packet-based control approach is effective in practice.

It is seen however that there is some difference between simulation and experimental results. Several possible reasons may contribute to this difference: 1) the identified model for the DC servo system may not be accurate enough; 2) the dead zone of the DC servo plant has not been considered; and 3) the measurement of the network-induced delays is not accurate in practice.

8.7 Conclusions

Networked control systems are the integration of conventional control systems and the communication networks. Therefore, a natural way to deal with the communication constraints in NCSs is to put the problem under the co-design framework–design with the integration of control theory and communication technology. Motivated by this co-design angle and benefited from the observation of the packet-based transmission in the networked control environment, we are able to propose the so-called packet-based communication and control co-design framework for networked control systems. By showing its effectiveness in dealing with the communication constraints including the network-induced delay, data packet dropout and data packet disorder simultaneously, theoretically, numerically, and experimentally, we are on our way torwards a unified approach to networked control systems, and consequentely the convegence of control, communication and computation in such an exciting era featured by ubiquitous networks, ubiquitous control.

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