SCIENCE CHINA
Technological Sciences

Special Topic: Network Science and Engineering
• **Article** •

January 2016 Vol.59 No.1: 72–80
doi: 10.1007/s11431-015-5977-y

Dynamic data packing towards the optimization of QoC and QoS in networked control systems

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Received July 1, 2015; accepted October 20, 2015; published online December 16, 2015

A class of networked control systems is investigated whose communication network is shared with other applications. The design objective for such a system setting is not only the optimization of the control performance but also the efficient utilization of the communication resources. We observe that at a large time scale the data packet delay in the communication network is roughly varying piecewise constant, which is typically true for data networks like the Internet. Based on this observation, a dynamic data packing scheme is proposed within the recently developed packet-based control framework for networked control systems. As expected this proposed approach achieves a fine balance between the control performance and the communication utilization: the similar control performance can be obtained at dramatically reduced cost of the communication resources. Simulations illustrate the effectiveness of the proposed approach.

networked control systems, packet delay variation, dynamic data packing, quality of control, quality of service

Citation: Kang Y, Zhao Y B. Dynamic data packing towards the optimization of QoC and QoS in networked control systems. Sci China Tech Sci, 2016, 59: 72–80, doi: 10.1007/s11431-015-5977-y

1 Introduction

Networked control systems (NCSs), i.e., control systems that are closed via some form of communication networks, have been one of the most important research themes in recent years. This popularity should be credited to the distinct features which are native to NCSs but are not usually seen in other types of control systems. These features include, for example, the easy maintenance, flexible control structure, reduced implementation cost, and so on [1–4], most of which are brought by the use of the communication networks in NCSs. However, in the meanwhile we see that the inclusion of the communication networks into conventional control systems, though forms a novel redesigned framework for control systems, does complicate the system design and then consequently introduce fundamental theoretical and practical challenges to conventional control theory and engineering. Therefore, work has to be done before NCSs can be applied widely as a reliable control strategy and one of the key fundamental techniques for next era automation applications such as the Internet of Things, mobile and industrial robotics, remote surgery, etc., just to name a few [5–8].

As have been widely acknowledged nowadays, the so-called communication constraints in NCSs, including, for example, network-induced delay, data packet dropout, data rate constraint, etc. present great challenging difficulties for

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*Corresponding author (email: ybzhao@zjut.edu.cn) the control engineers and theorists [9–11]. From the perspective of control engineering, NCSs differ from conventional control systems due to the inclusion of the communication networks which consequently introduce the aforementioned communication constraints. Then one has to address the following key question in order to bring the NCS technology to the practice: that is, under the communication constraints, how can the control system performance be optimized? The problem is so asked, implying the fact that in the early days of the development of NCSs, the communication constraints are typically regarded as some given constraints and conditions to the control system. As long as these conditions can be formulated within conventional control system framework, most existing control theories and algorithms can then be applied straightforwardly without many difficulties. The control theories and algorithms that have been successfully applied to NCSs include, for example, time delay system theory [12–17], switch system theory [18–21], sampled-data system theory [22–25] just to name a few. Another type of work is slightly different from the above, where the optimal utilization of the given communication resources is considered, and thus the communication network has been taken more use of, and the resulting closed-loop system is also different from a typical control system but still within the general control framework, which then forms a control strategy named “co-design” for NCSs [26–29].

It is observed that a common basis of these existing works is that the control system and the communication networks in NCSs are separated from each other, and the interactions among the subsystems are neglected. Despite the much simplified model and consequently the analysis tools, it is appreciated that NCSs involves control systems and communication networks at the same time, and therefore a global view and consequently an integrative approach should be of much value to the community. Different from the local picture, from a global point of view, the design considerations of a specific NCS involve not only the quality of control (QoC) of this NCS, but also the overall quality of service (QoS) of the communication network [30–33]. By saying the overall QoS, we mean that an optimal design, other than the optimization of the QoC, ought to reduce the consumption of the communication resources as much as possible in the meanwhile, in order that the performances of other systems which share the same communication network can also be optimized. This global view thus leads to a new challenge of designing NCSs subject to the balance between the QoC of the control system and the QoS of the communication network [34,35], which have not been seen in conventional control system theories.

Within this research line here we consider an NCS configuration where the controller-to-actuator channel of the NCS is shared with other applications, i.e., the data packets used to send the control signals compete with other application for the access of the communication network. We measure the communication resource that the considered control system uses by the data size required to encode the control signal. With this assumption, we observe two extreme cases in terms of the usage of the communication resources. The minimum usage is by most conventional control methods, which typically use only a data size able to encode one step control signal. On the other hand, the maximum usage is the recently reported packet-based control approach, which uses all the capacity of the data packet to encode multiple steps of the control signals [36]. Not surprisingly, the packet-based control approach results in a better system performance at the cost of increasing the usage of the communication resources. By investigating further the characteristics of the delay variation in such NCSs, in this work we are able to show that the usage of the communication resources can be dramatically reduced while at the same time maintaining the system performance at an acceptable level. This achievement is made based on an observation on the variation of the data packet delay, which is believed to be roughly piecewise constant at a large time scale. This observation then enables the design of a dynamic data packing strategy, allowing the most efficient use of the communication resources. The essential idea is to send the control signal only when a dramatic change of the data packet delay occurs. Due to the piecewise constant feature of the data packet delay, such a strategy reduces greatly the communication resource requirement, but can still maintain an acceptable control performance.

The remainder of the paper is organized as follows. Section 2 introduces relevant background information and formulates the problem of interest. Then the dynamic data packing scheme based on the packet delay variation is presented in Section 3. Within this framework an illustrative controller is designed in Section 4 using a model predictive control method. Numerical examples in Section 5 validate the proposed approach and Section 6 concludes the paper.

2 Preliminaries and problem formulation

2.1 The system under consideration

The system structure of a typical NCS is shown in Figure 1. Different from this standard structure we here consider a more complicated case illustrated in Figure 2. Notice that in Figure 1 the communication network is private to NCS while in Figure 2 NCS shares the communication network with other applications. These other applications can be various and may even not be control systems. More specifically, in this work it is assumed that the data packet sent from the controller to the actuator is shared among these multiple applications, as illustrated in Figure 3.

In Figure 3, other than the header and the trailer of the data packet, the effective payload is divided into multiple sections and the considered NCS only shares part of them and the amount that NCS uses can also vary with the

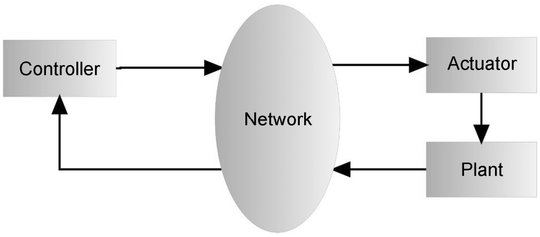

Figure 1 The typical system structure of a networked control system. The communication network is private to the networked control system.

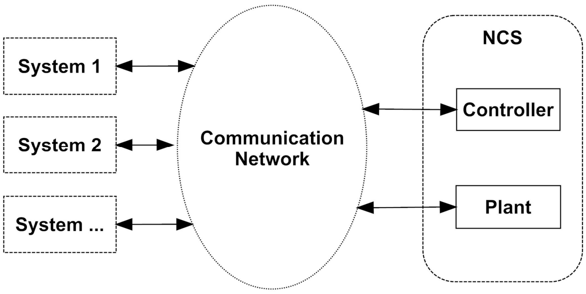

Figure 2 The considered networked control system in this work, where the network control system shares the limited communication resources with other applications.

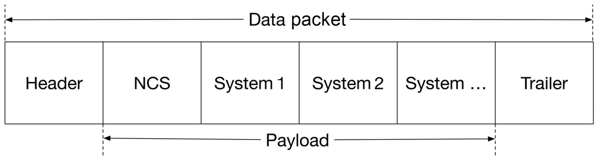

Figure 3 The structure of a typical data packet, where the effective payload is shared between the controller-to-actuator link of the networked control system and other applications.

availability of the communication resources.

In order to focus mainly on the shared communication resources induced challenges rather than the plant dynamics, the following linear nominal system model for the plant is therefore adopted:

$$x(k+1)=Ax(k)+Bu(k), \tag{1}$$

where $x\in R^n$ is the system state, $u\in R^m$ is the control input, and $A\in R^{n\times n}$ and $B\in R^{n\times m}$ are the system matrices. For simplicity we consider only such a nominal system model without the observation system, but it is worth pointing out that the implementation from the proposed scheme in this work is independent of the plant model. The scheme more focuses on the communication side and can virtually apply to any plants, meaning that the simple linear system model here is only for introductory purpose.

2.2 The problem and the objective

From the control engineering perspective, a controller is designed to meet certain control objectives such as stability, robustness, or some other optimization indexes of the system. For this purpose, we have already seen considerable control strategies proposed for conventional control systems. Even for NCSs, if the characteristics of the communication network are given a prior as certain parameter to the control system, the same methodology can still be applied, as can be seen in most existing work on NCSs.

The system setting in Figure 2 however proposes a different challenge. As this system involves closely both control and communication, a system level design then should try to find the balance between the two. We term the contribution of NCS to the usage of the communication network, i.e., reducing the usage of the data packet, as the contribution of the quality of service to the communication network. The overall objective can then be written in an informal way as

$$\max QoC \text{ and } \max QoS. \tag{2}$$

We state the problem of interest as to design appropriate control strategy such that the combined objectives in eq. (2) can be optimized.

For the usage of the payload of the data packets as illustrated in Figure 3 by the existing control algorithms, we observe two extreme cases.

Firstly, most conventional controllers typically produce a single step of the control signal at each step, which is then sent through the communication network in one data packet, i.e.,

$$B_{\min} =: B_c,$$

where B_c represents the data size required for encoding a single step of the control signal for the considered NCS, and $B_{\min}$ implies that this case uses the minimum amount of the data size.

On the other hand, the packet-based control approach takes use of much more payload of the data packet [36]. In fact, at each time step this approach will produce $i+1$ steps of control predictions where i is the upper bound of the round trip delay. These control predictions are then packed into one data packet and sent simultaneously to the actuator, i.e.,

$$B_{\max} =: (\bar{\tau}+1)B_c \leqslant B_p,$$

where B_p is the payload of the data packet and $B_{\max}$ represents this maximum usage. The actuator is then able to select from the predicted control signals the one that corresponds to current delay, and in this way the communication constraints can be actively compensated for.

Our objective in this work is to find a fine balance between the above extreme usages of the payload of the data packet: A dynamic data packing scheme that uses the communication resources more efficiently than conventional control algorithms whilst maintaining a similar satisfactory system performance as the packet-based control approach.

3 The dynamic data packing scheme for networked control systems

The dynamic data packing scheme is presented in this section. The motivation of the scheme is due to one particular communication characteristics in the considered system setting, where the variation of the data packet delay can be regarded as roughly piecewise constant. We first discuss this feature in detail and then introduce the dynamic data packing scheme based on this feature.

3.1 Packet decay variation in networked control systems

We first introduce the formal definition of the variation of the data packet delay, or "packet delay variation" of the communication network in Figure 2. As defined in ITU-T Recommendation Y.1540, packet delay variation is to refer the difference in end-to-end delay in a data flow with any lost packets being ignored [37]. In our system setting, we are interested in two packet delay variations, that is, the sensor-to-controller channel and the controller-to-actuator channel, respectively. Packet delay variation is then interpreted as the variations of the delays in the two channels, where data packet dropout and disorder are simply ignored.

Notice that in the current system setting where multiple applications share the communication network, packet delay variation is affected by two main factors, that is, the access to the communication network by the subsystems, and the variation of the data exchanges of a single subsystem. As discovered earlier [37], the data exchange requirement of a typical application is usually stable, and the joining and leaving of subsystems should not be too frequent neither, it is therefore reasonable to assume that the packet delay variation should be approximately piecewise constant. With such an assumption, the delay remains approximately constant for a certain time period, switches suddenly to another constant and remains there again, as illustrated in Figure 4. This assumption is stated formally as follows.

Assumption 1. The packet delay variation of the communication network in the system as illustrated in Figure 2 is approximately piecewise constant.

The piecewise constant assumption of the packet delay variation is the fundamental basis of the work proposed here. Before proceeding further with the dynamic data packing scheme to be presented later, we introduce another assumption which is also essential for the proposed scheme.

Assumption 2. The data transmission in both the sensor-to-controller and the controller-to-actuator channels have the similar communication characteristics; in particular, the similar packet delay variations.

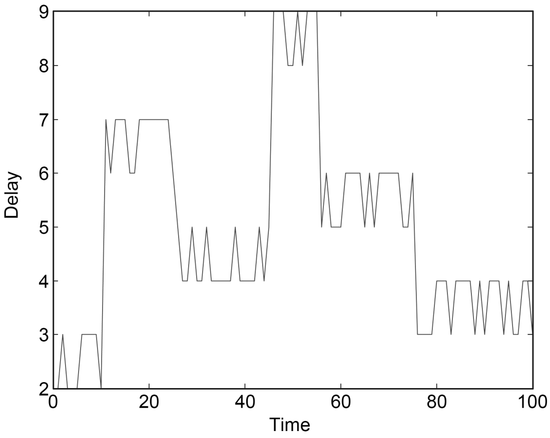

Figure 4 The packet delay variation can be piecewise constant in practice.

The underlying rationality of the above assumption is that in our system setting, the data packets in the sensor-to-controller channel and the controller-to-actuator channel use the same communication network, as shown in Figure 2. With this network configuration, Assumption 2 is thus reasonable as long as the characteristics of the communication networks are relatively stable. Assumption 2 implies that at any specific time a data packet transmitted from two nodes, regardless of the directions, should experience the same (similar) possibility of packet delay variations.

3.2 The dynamic data packing scheme for networked control systems

One may now realize that the two assumptions in the last subsection lead to an important conclusion: the delay in the controller-to-actuator channel can be reasonably estimated based on the delay information in the sensor-to-controller channel. This works as follows. As soon as the delay in the sensor-to-controller channel is known, Assumption 1 ensures that this delay will remain within a small range of variation for a relatively long time period. Then, Assumption 2 means that the controller-to-actuator delay is also not significantly different from this delay. As a result, we may estimate the delay in the controller-to-actuator channel based on that in the sensor-to-controller channel.

The dynamic data packing scheme can then be designed, as follows.

Delay estimation. We label each data packet sent from the sensor with a time stamp of the current time, a technique widely used in NCSs [36], and as a result the delay in the sensor-to-controller channel is known to the controller provided that the controller and the sensor are time synchronized which is assumed to be held in this work. The delay in the controller-to-actuator channel is then estimated in the following way:

$$\hat{\tau}_{ca,k} \in [\tau_{sc,k} - \tau_\delta, \tau_{sc,k} + \tau_\delta], \tag{3}$$

where τ_δ represents the packet delay variation, $\tau_{sc,k}$ and

$\hat{\tau}_{ca,k}$ are the measured and estimated delays in the sensor-to-controller channel and the controller-to-actuator channel, respectively. Both delays are measured or estimated at time k at the controller side.

Control predictions calculation. As in the classic packet-based control approach, we need to calculate a forward control sequence which consists of multiple steps of the control predictions, and then send them together in one data packet to the actuator. Using classic packet-based control approach, this forward control sequence usually covers control predictions with at least the upper bound of the round trip delay, in order that the network induced delay can be actively compensated for [36]. One may realize that this forward control sequence may have to contain a large amount of data to be sent to the actuator and cause great burden to the communication network. With the delay estimation technique in this work, we dramatically reduce the length of the forward control sequences to only $2\tau_\delta+1$ control predictions starting from time $k+\tau_{sc,k}-\tau_\delta$, as follows:

$$\begin{aligned}&U\left(k|k-\tau_{sc,k}\right)\\&=\left[u\left(k+\tau_{sc,k}-\tau_\delta|k-\tau_{sc,k}\right)\cdots u\left(k+\tau_{sc,k}|k-\tau_{sc,k}\right)\right.\\&\quad\left.\cdots u\left(k+\tau_{sc,k}+\tau_\delta|k-\tau_{sc,k}\right)\right],\end{aligned}\tag{4}$$

where all the control predictions are calculated based on the state information $x(k-\tau_{sc,k})$ at time k at the controller side. For simplicity we consider the use of a simple state feedback controller, and then the control signals in eq. (4) can be constructed as follows:

$$\begin{aligned}&u\left(k+\tau_{sc,k}+i\mid k-\tau_{sc,k}\right)\\&=K\left(k+\tau_{sc,k}+i\mid k-\tau_{sc,k}\right)x\left(k-\tau_{sc,k}\right),\end{aligned}\tag{5}$$

where $K\left(k+\tau_{sc,k}+i|k-\tau_{sc,k}\right)$ $i=-\tau_\delta,\cdots 0,\cdots,\tau_\delta$ are the feedback gains with respect to different delays in the controller-to-actuator channel. Then the general form of the forward control sequence in eq. (4) can be written as follows:

$$\begin{aligned}&U_x\left(k|k-\tau_{sc,k}\right)\\&=\left[K\left(k+\tau_{sc,k}-\tau_\delta|k-\tau_{sc,k}\right)\cdots K\left(k+\tau_{sc,k}|k-\tau_{sc,k}\right)\right.\\&\quad\left.\cdots K\left(k+\tau_{sc,k}+\tau_\delta|k-\tau_{sc,k}\right)\right]x\left(k-\tau_{sc,k}\right),\end{aligned}\tag{6}$$

where the symbol T represents the transpose of a matrix.

Delay compensation. Using the classic packet-based control approach, the appropriate control signal from the forward control sequence is selected according to current network condition. This is implemented by a device called "control action selector". This can be done since the forward control sequence contains enough control predictions so that for any control-to-actuator delay the corresponding control signal can always be found in this forward control sequence. However, this is not the case using the much shortened forward control sequence in eq. (4). In fact, one can easily see that the control signal that can exactly compensate for the current delay is not in the forward control sequence as long as the absolute difference of the real delay in the controller-to-actuator channel, $\tau_{ca,k}$ and the estimated delay, $\hat{\tau}_{ca,k}$, is larger than τ_δ. To overcome this difficulty, we deploy a controller switch scheme by designing an additional static feedback gain K offline, as typically done in conventional algorithms. This controller is used to complete the dynamic data packing scheme under certain conditions. Similar to the control action selector in the classic packet-based control approach, a "gain scheduler" is implemented at the actuator side to select the appropriate control actions. At time k at the actuator side (notice that the forward control sequence was calculated at time $k-\tau_{ca,k}$ at the controller side), the control signal is determined by the gain scheduler as follows:

$$\begin{aligned}&K\left(k|k-\tau_k\right)x\left(k-\tau_k\right),\left|\tau_{ca,k}-\tau_{sc,k}\right|\leqslant\tau_\delta\\&Kx\left(k-\tau_k\right),\ \text{otherwise},\end{aligned}\tag{7}$$

where $\tau_k=:\tau_{sc,k}+\tau_{ca,k}$ is the round trip delay. With the designed static controller, the system will never run in an open-loop fashion as it closes the control loop whenever the dynamic data packing scheme fails to do so.

The implementation procedure of the dynamic data packing scheme for NCSs can now be organized as follows, and its schematic structure is depicted in Figure 5.

Algorithm 1. Dynamic data packing for networked control systems.

S1. The sensor samples the plant and sends the sampled data to the controller with time stamps.

S2. The delay in the controller-to-actuator channel is estimated by eq. (3), based on which the controller produces the forward control sequence by eq. (6), and sends it to the actuator.

S3. The actuator applies the control signal determined by eq. (7) to the plant.

Remark 1. Flexibility of the dynamic data packing scheme. One may notice that the essential pre-requirement for the dynamic data packing scheme is that the delay in the controller-to-actuator channel has to be estimated. In the present work it was done based on Assumptions 1 and 2 in Subsection 3.1, but any other ways that can provide a reasonable estimation of the delay will do the job, and can be easily fitted into the dynamic data packing scheme. This means that the implementation of Algorithm 1 can be relatively flexible in practice.

Remark 2. Data packet dropout and disorder. The classic packet-based control approach deals not only with networked induced delay, but data packet dropout and disorder in the unified framework. Though not explicitly mentioned, data packet dropout and disorder can also be considered

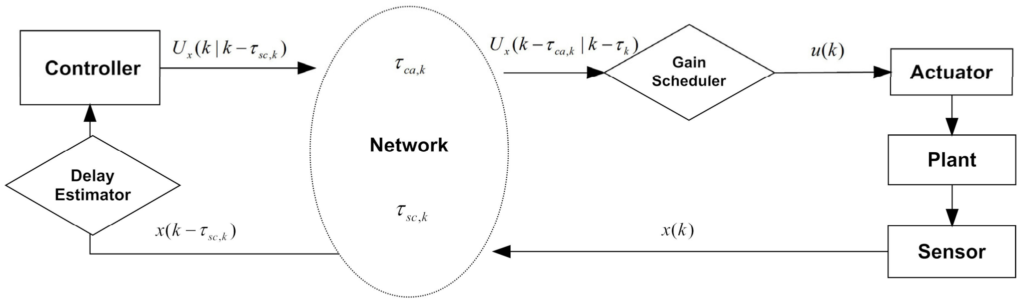

Figure 5 The system structure of networked control systems with the dynamic data packing scheme.

using the dynamic data packing scheme without any further difficulties. One may notice, however, data packet dropout and disorder do increase the packet delay variation, τ_δ, and consequently the more often use of the static feedback gain K, and therefore the system performance may be degraded due to these communication constraints. For more details of the treatment of the data packet dropout and disorder within the packet-based control framework, please refer to refs. [36,38].

Remark 3. The QoS improvement. In terms of the usage of the effective payload of the data packet, we are able to establish the following relation:

$$B_{\min} : B_{\mathrm{m}} : B_{\max} = 1 : (2\tau_\delta + 1) : (\overline{\tau} + 1),$$

where B_{m}, the usage of the payload by the dynamic data packing scheme, is in the middle of conventional control algorithms and the packet-based control approach. Since the packet delay variation τ_δ is usually much smaller than the delay upper bound $\overline{\tau}$, the dynamic data packing scheme should be able to significantly reduce the usage of the payload. In addition, we may regard conventional control algorithms and the packet-based control approach as two extreme cases in terms of the usage of the payload (for example, let $\tau_\delta = 0$ and $\tau_\delta = \overline{\tau}/2$, respectively). From this perspective one may say that the dynamic data packing scheme can serve as a unified framework in terms of the usage of the communication resources in NCSs.

4 A model predictive based controller

The dynamic data packing scheme proposed in the last section is designed subject to the control purpose but more within the communication side. From the control engineering perspective, it is a general framework for the system setting in Figure 2, since any controller design method, as long as it can produce appropriate forward control sequence, can be used within this framework. This is the flexibility of the framework which offers great freedom to the engineers and theorists for the whole systems design.

In this section we design a model predictive control based controller as an example. As is well-known, model predictive control is a finite horizon optimal control method. With this method a finite horizon optimization problem is solved at every step, where the first control input of the resulting control predictions is applied while others are discarded. Model predictive control is an effective way to deal with noises, uncertainties and constraints at an affordable cost due to its unique receding horizon optimization that is done repeatedly at each step. In the meanwhile, the model predictive controller produces a sequence of control predictions which makes it naturally fit for the calculation of the forward control sequence in the packet-based control approach.

The objective function of the model predictive controller at time k at the controller side, denoted by J_k, is designed as follows:

$$\begin{aligned} J_k &= X^{\mathrm{T}}\left(k|k-\tau_{sc,k}\right)Q_{\tau_{sc,k}}x\left(k|k-\tau_{sc\,k}\right) \\ &\quad + U^{\mathrm{T}}\left(k|k-\tau_{sc,k}\right)R_{\tau_{sc,k}}U\left(k|k-\tau_{sc,k}\right), \end{aligned} \tag{8}$$

where

$$\begin{aligned} &U\left(k|k-\tau_{sc,k}\right) \\ &= \left[u\left(k-\tau_{sc,k}\,|\,k-\tau_{sc,k}\right)\cdots u\left(k+N-1|k-\tau_{sc,k}\right)\right]^{\mathrm{T}} \end{aligned}$$

contains the control predictions to be determined,

$$\begin{aligned} &X\left(k|k-\tau_{sc,k}\right) \\ &= \left[x\left(k-\tau_{sc,k}+1|k-\tau_{sc,k}\right)\cdots x\left(k+N|k-\tau_{sc,k}\right)\right]^{\mathrm{T}} \end{aligned}$$

is the predictive state trajectory, $Q_{\tau_{sc,k}}$ and $R_{\tau_{sc,k}}$ are weighting matrices with appropriate dimensions and N is the prediction horizon. In the present work we require that $N > \tau_{sc,k} + \tau_\delta$. This requirement is to ensure that the control predictions from $k+\tau_{sc,k}-\tau_\delta$ to $k+\tau_{sc,k}+\tau_\delta$ are available from (11). A larger N usually leads to a better system performance as it increases the optimization horizon, but in the meanwhile increasing N may increase the computational complexity greatly which is one key constraint of the model predictive control method. Therefore, a properly selected N should be subjected to both constraints of the system performance and the computation resources.

Similar to standard model predictive controllers, the predictive states at time k are calculated by iteration for $j = 1, 2, \cdots, N + \tau_{sc,k}$, as follows:

$$\begin{aligned} & x\left(k-\tau_{sc,k}+j \middle| k-\tau_{sc,k}\right) \\ & = A^{j} x\left(k-\tau_{sc,k}\right)+\sum\nolimits_{l=0}^{j-1} A^{j-l-1} B u\left(k-\tau_{sc,k}+l \middle| k-\tau_{sc,k}\right), \end{aligned}$$

where $u\left(k-\tau_{sc,k} | k-\tau_{sc,k}\right)=u\left(k-\tau_{sc,k}\right)$. Notice that both $u(k-\tau_{sc,k})$ and $x\left(k-\tau_{sc,k}\right)$ are available to the controller.

Then in the vector form the predictive states can be written as

$$X\left(k | k-\tau_{sc,k}\right)=E_{\tau_{sc,k}} x\left(k-\tau_{sc,k}\right)+F_{\tau_{sc,k}} U\left(k \mid k-\tau_{sc,k}\right), \quad (9)$$

where $E_{\tau_{sc,k}}=\left[A^{\mathrm{T}} \cdots\left(A^{N+\tau_{sc,k}}\right)^{\mathrm{T}}\right]^{\mathrm{T}}$ and $F_{\tau_{sc,k}}$ is a $\left(N+\tau_{sc,k}\right)$ $\times(N+\tau_{sc,k})$ block lower triangular matrix with its non-null elements defined by $\left(F_{\tau_{sc,k}}\right)_{ij}=A^{i-j} B, j \leqslant i$.

The optimal forward control sequence is calculated by substituting eq. (9) into eq. (8) and minimizing J_k. This leads to a state feedback controller, as follows:

$$U\left(k | k-\tau_{sc,k}\right)=K_{\tau_{sc,k}} x\left(k-\tau_{sc,k}\right), \quad (10)$$

with the feedback gain vector $K_{\tau_{sc,k}}$ as follows:

$$K_{\tau_{sc,k}}=\left(F_{\tau_{sc,k}}\right)^{\mathrm{T}} Q_{\tau_{sc,k}} F_{\tau_{sc,k}}+R_{\tau_{sc,k}}^{-1} F_{\tau_{sc,k}}^{\mathrm{T}} Q_{\tau_{sc,k}} E_{\tau_{sc,k}}. \quad (11)$$

The forward control sequence as in eq. (6) can finally be defined by selecting appropriate items from $K_{\tau_{sc,k}}$ as defined in eq. (11).

Remark 4. As mentioned earlier the model predictive controller is only an introductory example to complete the design of the dynamic data packing scheme. Any appropriate control methods that can result in a desirable forward control sequence can also be used, which will also be our future work.

5 Numerical examples

For illustration purpose we consider the system in eq. (1) with the following system matrices borrowed from ref. [36] to show the effectiveness of the proposed approach in this paper,

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

We set the initial state of the considered system as $x_0=\left[x_1(0) x_2(0)\right]^{\mathrm{T}}=[-11]^{\mathrm{T}}$. The system is simulated for 150 time steps. During the simulation the delay levels are switched at time instants 10, 25, 45, 55, 75, 100, with the corresponding basic delay levels being 2, 6, 4, 8, 5, 3, respectively. The variation of the packet delay is assumed to be $\tau_{\delta}=2$, meaning that the actual delay is stochastically varying around the basic delay level by τ_{δ}.

In order to demonstrate the effectiveness of the dynamic data packing scheme on a comparison basis, we consider both a linear quadratic regulator (LQR) controller and the classic packet-based controller. The LQR controller is designed without the consideration of data packet delay or the delay variation in the NCS, as follows:

$$K_{LQR}=[-0.6893-1.2618].$$

The packet-based controller is obtained as in Section 4. At each time step a forward control sequence with 17 (where $\bar{\tau}=16$) control predictions is produced which is then sent to the actuator in one data packet. The delay-dependent control gains are as follows:

$$K_{DB}=-\left(\begin{array}{c|c} 0.6151 & 1.1712 \\ 0.5051 & 1.0490 \\ 0.4088 & 0.9357 \\ 0.3252 & 0.8309 \\ 0.2530 & 0.7341 \\ 0.1912 & 0.6447 \\ 0.1389 & 0.5624 \\ 0.0951 & 0.4866 \\ 0.0593 & 0.4168 \\ 0.0306 & 0.3528 \\ 0.0084 & 0.2939 \\ 0.0077 & 0.2400 \\ 0.0183 & 0.1905 \\ 0.0238 & 0.1452 \\ 0.0244 & 0.1037 \\ 0.0205 & 0.0659 \\ 0.0123 & 0.0314 \end{array}\right).$$

The dynamic data packing scheme generates different delay-dependent control gains for each sensor-to-controller delay. For example, the controller gain is given as follows for $\tau_{sc}=7$:

$$K_{DP}=\left(\begin{array}{c|c} 0.0245 & -0.3191 \\ 0.0423 & -0.2737 \\ 0.0556 & -0.2329 \\ 0.0649 & -0.1963 \\ 0.0705 & -0.1635 \end{array}\right).$$

Note that the dynamic data packing scheme uses also the LQR controller to close the control loop, whenever the

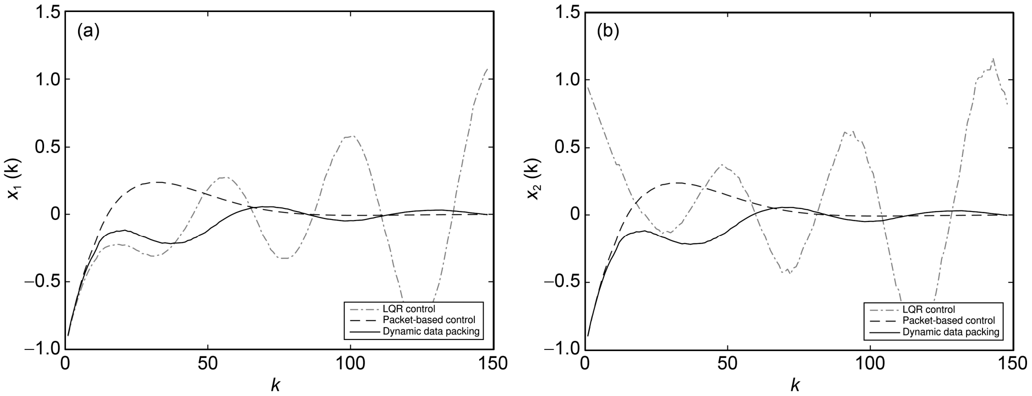

Figure 6 Both the standard packet-based control approach and the dynamic data packing scheme stabilize the system but conventional LQR controller fails so. (a) State evolutions of the networked control system, showing x_1; (b) state evolutions of the networked control system, showing x_2.

preferred delay-dependent controller is not available to the actuator.

The system evolutions and the control signals of the system under the LQR controller, the packet-based control approach and the dynamic data packing scheme are shown in Figures 6 and 7, respectively. The system is unstable in the presence of the LQR controller, and is stable for both the packet-based control approach and the dynamic data packing scheme. As expected the system response with the dynamic data packing scheme experiences more fluctuations but the overall performance is not much worse than the packet-based control approach.

We know that the packet-based control approach uses 17 control predictions at every time step, while the forward control sequence of the dynamic data packing scheme contains only $2\tau_\delta + 1 = 5$ control predictions. Therefore, the dynamic data packing scheme consumes only around 30% of the communication resources consumed by the packet-based control approach. This is a significant reduction of the usage of the communication resources, especially when we notice that the system performance can still be maintained at an acceptable level at this much reduced usage of the communication resources.

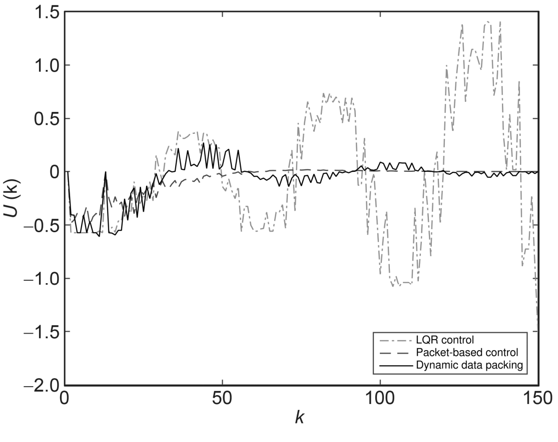

Figure 7 The control signal used by the three different controllers.

6 Conclusions

Though the optimization of the control system performance is usually the primary objective in most studies on networked control systems, the practical implementation should include the usage of the communication resources as part of the objective function. Towards the optimization of the system subject to both performance requirements of the control system and the communication network, we proposed a dynamic data packing scheme for networked control systems, inspired by the approximately piecewise constant feature of the data packet delay in the communication networks. We then demonstrate its effectiveness by comparing it with conventional control algorithms and the classic packet-based control approach, and as expected a better balance between the control and communication performance is achieved. From a more general perspective conventional control algorithms and the classic packet-based control approach are just two extreme cases of the proposed dynamic data packing scheme, in terms of the usage of the effective payload of the data packet. This then makes the dynamic data packing scheme a unified framework towards this balance. Future work will focus on the controller design and system performance analysis under this framework, to enable it widely applicable in practice.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 61422307, 61174061 & 61304048), the Scientific Research Starting Foundation for the Returned Overseas Chinese Scholars, Ministry of Education of China, the National Hi-Tech Research and Development Program of China (“863” Project) (Grant No. 2014AA06A503), the Youth Innovation Promotion Association, Chinese Academy of Sciences, in part by the Youth Top-Notch Talent Support Program, and the 1000-Talent Youth Program and Zhejiang 1000-Talent Program.

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