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Coping with Time Delays in Networked Control Systems

Hitay Özbay

Abstract— **In networked control systems, where controller and plant exchange information over a communication network, performance of the feedback system depends on certain properties of the communication channels. For example, packet loss, network delay and delay jitter have negative effect on networked system performance. Depending on the communication infrastructure, different mechanisms are implemented to reduce the packet loss rate and network induced delay in communication networks. In this paper, one of these mechanisms, namely, buffer/queue management is studied. It will be shown that techniques from robust control of uncertain time delay systems can be used effectively. Simpler low order controllers (PI and PID) are also considered. The effect of controller parameters on various performance metrics are illustrated.**

I. Introduction

This paper is a companion to the semi-plenary talk to be given by the author at the 19th International Symposium on Mathematical Theory of Networks and Systems (MTNS 2010) in Budapest, Hungary, July 2010. A brief summary of the problems to be considered is given here, along with a list of references where most of the results to be presented are taken from. The list is by no means complete, and the problems discussed here touch upon a small portion of all the issues associated with networked control systems.

The performance of a networked control system depends on certain properties of the communication channel. The packet loss and network induced delay adversely affect the performance. Typically, the network induced delay is time varying, uncertain and its magnitude is large enough that it cannot be ignored at the controller design stage (unless, of course, the feedback system can be made stable independent of time varying time delays). In this talk we discuss ways to *control the communication network* so that packet loss is as small as possible, and the network induced delay is as close to a constant as possible. One of the most important factors causing packet loss and large varying delay is the congestion. When congestion occurs buffers may get full (in which case the packets are dropped), that leads to re-transmission and large queuing delays (large compared to propagation and computation/packet processing delays). Therefore, congestion control mechanisms, where queue management is done, play important roles in reducing the packet loss rate and the variation (and magnitude) of the delay. In this talk different types of buffer management schemes will be studied. It will be shown that techniques from robust control of uncertain time delay systems can be used effectively.

H. Özbay is with Dept. of Electrical and Electronics Engineering, Bilkent University, Ankara, TR-06800, Turkey; currently on sabbatical leave at INRIA Paris-Rocquencourt, France, hitay@bilkent.edu.tr

Many survey papers (and special issues of the leading control journals) have already been published on networked control systems in general; see for example [34], [110] where several issues such as channel limitations, sampling, network delay, and packet dropouts are reviewed. Earlier, [16] studied control over communication networks with queuing delays, where the motivating application was automotive systems. Sampled-data networked control system framework is considered in [28], [29], [42], [58], [109], [111], [113] with problems related to network induced delays, data packet dropouts and quantization. A scheduling method is proposed in [51] to control the delay. A recent work on comparison of stability results in this context is [36]. Several issues related to non-uniform sampling are handled in [25], [26], [27], [69], [73], [92]. Some of these problems can be solved by considering modeling the system as discrete-time switched linear system with varying delays, [35]. A delay-independent stability result is obtained for networked control systems in [38]. There are also several works devoted to network delay measurement and estimation, [98], Kalman filtering under uncertain delay, [88] and multi-hop configuration, [101].

When the control is done over a network which is shared by others for other applications, fairness in rate allocation becomes an important constraint in buffer management. For example, real-time transmission of multilayer video over ATM networks also requires buffer management, [86]. Rate allocation and buffer management for differentiated services is discussed in [59]; [89] shows that link utilization can be traded for queuing delays. In this talk, rate allocation in ATM networks and active queue management (AQM) for TCP flows will be reviewed. For recent results on AQM see [10], [84], [100], [112] and their references. See [22] for methods other than TCP for flow control. Control theory based analysis of TCP-AQM is done in [39], [40], [61], [82], [67], [68], see also their references.

The results to be presented here are taken from the author's joint work with several colleagues; this is a series of collaborations which started in 1998 with [75] and continued until recently, [9], [13], [20], [21], [71], [79], [80], [81], [82], [83], [95], [97], [104], [105].

In the next section a simple mathematical model of a networked control system is given and associated buffer management problems are defined for control of networks. In Section III rate assignment in ATM networks and active queue management for TCP flows are discussed. The reader can find the full details of the results in cited references. Due to copyright issues some of the results to be shown in the talk cannot be included in this companion paper.

II. Networked Control System and Control of Networks

Consider the system shown in Figure 1 where the plant is controlled over a network.

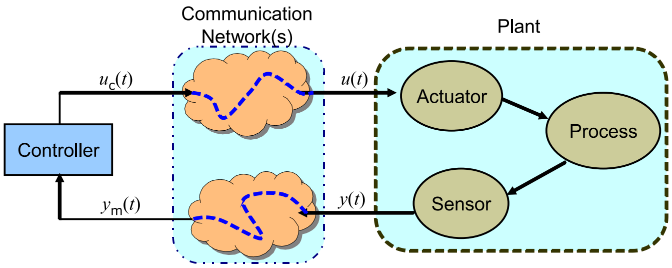

Fig. 1. Control over a network.

Most of the problems studied within the framework of networked control systems arise from the fact that

$$u_c(t) \neq u(t) \quad \text{and} \quad y_m(t) \neq y(t).$$

A simple representation of the effect of the network on these signals is

$$\begin{aligned} u(t) &= u_c(t - \tau_f(t)) + \vartheta_f(t) \\ y_m(t) &= y(t - \tau_b(t)) + \vartheta_b(t) \end{aligned}$$

where $\tau_f(t)$ and $\tau_b(t)$ represent the network induced delay, and $\vartheta_f(t)$ and $\vartheta_b(t)$ represent all the other uncertainty due to sampling-holding, quantization, scheduling, packet loss, etc. If any of these functions $\tau_f(t)$, $\tau_b(t)$, $\vartheta_f(t)$, $\vartheta_b(t)$ is large, then performance of the networked control system can be poor. Variation of the delays also adversely affect the performance.

Time delays $\tau_f(t)$ and $\tau_b(t)$, consist of propagation, processing and queuing delays. In a congested network, once the routing is established for a specific connection, the most important component of the network induced delay is the part which is due to queuing. Therefore, it is important to control the queue in the congested link(s), to keep the delay at an acceptable level. Another important reason to do the queue management is to make sure that the buffers do not get full; this is to prevent packet loss and re-transmission. Thus, queue management is also helpful in making $\vartheta_f(t)$, $\vartheta_b(t)$ small. In the next section we concentrate on what goes on inside the network and discuss queue management schemes.

III. Queue Management in Networks

Let us consider a generic data communication set-up shown in Figure 2. With respect to the networked control system shown in Figure 1, we can think of one of the senders to be the controller sending u_c (respectively the sensor sending y) and the corresponding receiver to be the actuator receiving u (respectively the controller receiving y_m). All the other senders and receivers are other users sharing the same network/link for other applications. The senders adjust their packet sending rates based on the acknowledgment signals transmitted by the receivers.

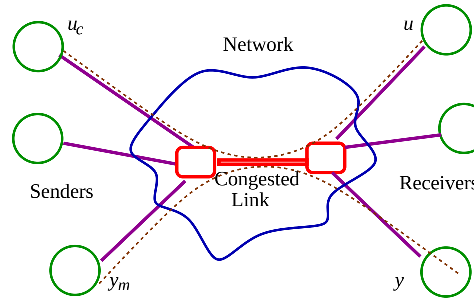

Fig. 2. A communication network.

Using fluid flow approximation, the queue at the bottleneck (congested) link evolves according to

$$\dot{q}(t) = r_{\text{in}}(t) - c(t)$$

where $r_{\text{in}}(t)$ is the incoming data packet flow rate and $c(t)$ is the outgoing flow rate (available capacity of the link). As the packets pass through the network, they reach their destination with a forward time delay $h_f(t) = h_p + \frac{q(t)}{c(t)}$, where h_p is the propagation delay in the forward path, and $\frac{q(t)}{c(t)}$ is the queueing delay. Once the packets are received, acknowledgments are sent back; assuming they pass through the same network, with a separate buffer, which is almost always empty, the backward delay is $h_b \approx h_p$. So, we define the return-trip-time $RTT(t) = h(t) = 2h_p + \frac{q(t)}{c(t)}$. Typically, the input flow rate is set by the controller as a function of the "congestion information" relayed to the controller, delayed by $h(t)$. In other words, we may assume that $r_{\text{in}}(t) = r_c(t - h(t))$, where $r_c(t)$ is the assigned flow rate at time t (i.e. output of the controller). Thus, we have different plant models, depending on how this congestion information (feedback) is set. From the above discussion it is clear that queue evolution equation will contain a time delay which depends on the queue itself. More precisely,

$$\dot{q}(t) = r_c(t - h(t)) - c(t) \ , \qquad h(t) = 2h_p + \frac{q(t)}{c(t)}. \quad (1)$$

Analysis of these type of state dependent delay systems have been considered in the literature, see e.g. [18], [33], [62] and their references . But the controller design in this context is a difficult problem. So, typically, we assume that the delay has a nominal value, $h_o = 2h_p + q_o/c_o$, where q_o and c_o are the nominal values of the queue and the link capacity, respectively, and the variations of the delay is bounded.

For various types of network configurations and information available for feedback, stability analysis and controller design have been studied in the literature, see e.g. [1], [2], [3], [4], [5], [6], [7], [8], [11], [12], [23], [30], [44], [45], [47], [48], [49], [50], [52], [53], [54], [55], [57], [60], [65], [72], [77], [78], [85], [90] Some of these configurations are briefly discussed in subsections below.

A. Rate Control in ATM Networks

When the explicit queue information is fed back to the controller (as in ATM networks, see e.g. [14], [15], [43], [46],

[63]) $\mathscr{H}_\infty$-based robust controllers can be designed, [81], by using the uncertainty bound on the time delay and the time derivative of the delay. In this setting a linear time invariant controller is designed in such a way that with respect to (1) we have

$$R_c(s) = K(s)(Q(s) - Q_d(s))$$

where s denotes the Laplace transform variable $q_d(t)$ is the desired queue, and $K(s)$ is the $\mathscr{H}_\infty$ controller to be designed to achieve robust stability and queue tracking objectives, for details see [81]. Nominal time delays in each source-destination link are assumed to be the same in [81]. This assumption is relaxed in [95], and an $\mathscr{H}_\infty$ controller is designed using the approach proposed in [66]. Extension to multiple bottlenecks and decentralized control scheme appears in [13] and [71]. The controller of [81] assumes that the queue information is available for feedback and the capacity $c(t)$ of the congested link is unknown constant. On the other hand, changes in the behavior of the cross traffic (users sharing the same network link which are not controlled) the capacity may vary in an unknown fashion. In this case a two degree of freedom controller can be used:

$$R_c(s) = K_1(s)(Q(s) - Q_d(s)) + K_2(s)C(s)$$

where $K_2(s)C(s)$ generates $\widehat{c}(t+h_o)$ which is the predicted future value of $c(t)$; h_o is the nominal value of the RTT and K_2 is a causal capacity predictor which can be designed using different methods depending on the assumptions on the variations of $c(t)$, see [103], [104] for more details.

B. AQM for TCP Flows

In active queue management of TCP flows, feedback information is implicit: as data packets pass through the congested link, some percentage of them are marked according to the average queue level, and the sources adjust their rates according to the packet marks received, see [61] for more details and references. For this scenario there is a nonlinear time delay system model, [70], which has been linearized and used in various control schemes, [19], [40], [82], [87], [105], [106]. The underlying plant model changes slightly if a multi-level congestion notification is used, [21], [80], but the control analysis remains the same.

1) $\mathscr{H}_\infty$ Controller Design for AQM: The linearized model for TCP queue dynamics can be taken to be in the form

$$P(s) = K_o \, \frac{A(s)\ e^{-h_o s}}{1 + A(s)\ h_o s\ e^{-h_o s}}$$

where $A(s) = (W_o(h_o s)^2 + (W_o+1)h_o s + 2)^{-1}$ and K_o, W_o are constants. This model fits the $\mathscr{H}_\infty$ mixed sensitivity minimization problem solved in [24], [94], where one is interested in finding a stabilizing controller K for the plant P, minimizing

$$\left\| \begin{bmatrix} W_1(1+PK)^{-1} \\ W_2 PK(1+PK)^{-1} \end{bmatrix} \right\|_\infty .$$

The weights W_1 and W_2 are chosen in such a way that uncertainty in the time delay, number of users and link capacity are taken into account. See [82] for full details.

Typically the structure of the $\mathscr{H}_\infty$ controller for the plants in the form given above contains a distributed delay term (a subsystem with finite duration impulse response) and a PI part. The distributed term requires $[h/T_s]$ number of shift memory registers in digital implementation, where h is the RTT and T_s is the sampling time; this can be costly (hardware and software implementation point of view). Therefore, most practical implementations use PI/PID controllers only.

2) PID Controller Design for AQM: The first group of researchers who gave guidelines for PI gain selection for AQM of TCP flows was Hollot and his colleagues, [40]; this is embedded to ns-2, [74], as the default PI controller design, and serves as a benchmark. Since then, many variations and extensions have been published on this topic, see e.g. [31], [41], [67], [68], [93], [96] and their references.

Depending on varying network conditions one may want to use switched PI controllers for AQM, as discussed in [97] where the PID controller design method of [32] and [76] are used for unstable systems (including integrating processes) with time delays. Performance analysis in [97] is done with ns-2 simulations. Theoretical stability analysis of such a switched time delay system can be done using the results of [107], [108], where dwell time based stability conditions are obtained for switched delay systems. See also [17], [37], [56], [91], [99], [102] and their references for alternative conditions of stability for switched delay systems appearing in different applications, including networked control systems.

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