Available online at www.sciencedirect.com
ScienceDirect
Control Engineering Practice 15 (2007) 177–186
CONTROL ENGINEERING PRACTICE
www.elsevier.com/locate/conengprac

Reduction-based robust active queue management control

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Received 22 September 2005; accepted 31 May 2006
Available online 24 July 2006

Abstract

This paper is concerned with the design of improved active queue management (AQM) control schemes for time-delay systems taking into account explicitly the presence of delays in the controller design. A robust controller coping with uncertainties on the network parameters such as round-trip time and load variations is proposed. This is based on an appropriate robust reduction method for time-delay systems. A robust observer for time-delay systems is used to estimate online the average transmission window resulting in a robust output feedback stabilization scheme for AQM. The resulting control law is validated and tested firstly through numerical simulations and then pseudo-experimentally by network simulator (NS-2).

Keywords: Communication network; Active queue management; TCP congestion control

1. Introduction

In the past few years, networks have become an essential part of many engineering applications. A particularly cumbersome task when dealing with networks, for example with Internet, is to model, analyze and control the transient and steady-state behavior of traffic flows particularly at congested links. Recently, models have been proposed which approximate the packet transmission as a continuous flow with the aim of correctly estimating average steady-state variables such as transmission rates (Low, Paganini, & Doyle, 2002; Misra, Gong, & Towsley, 2000). These models have allowed the derivation of alternative congestion control techniques such as those proposed in Hollot, Misra, Towsley, and Gong (2002), Low et al. (2002). The control mechanism often used to prevent the congestion phenomenon is the transmission control protocol (TCP). During a TCP communication, the receiver sends back to the sender an acknowledgment signal for each packet which has been received. The time between the packet sending from the source and the reception of its acknowledgment is called round trip time (RTT). Namely, the TCP sender transmits W packets (W is labeled window size) and waits for their respective acknowledgments. If packets are acknowledged, the sender then increases W while if a packet is dropped (i.e. not acknowledged by the receiver), W is halved (multiplicative decrement). A more sophisticated flow control strategy, the so-called random early drop (RED) control, is achieved through a feedback mechanism based on marking (or dropping) packets according to the average queue length. This information when acknowledged by the receiver, allows the transmitter to increase or reduce its transmission rate in better accordance with the actual queue usage. This is a simple form of active queue management (AQM). The main advantages of RED control schemes are the elimination of flow-synchronization problems and the attenuation of traffic outbursts through the control of the average queue length. The principal disadvantage is the difficulty of tuning the control characteristic parameters. Another important limitation of RED–AQM is its lack of robustness against parameter variations and delays. Novel congestion control strategies have been proposed to improve the performance of standard TCP–RED algorithms (see for example Hollot, Misra, Towsley, & Gong, 2001 and references therein) and it has been shown that control theory can offer an invaluable set of tools to improve the performance of existing AQM schemes which can be seen as particular types of feedback control systems

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0967-0661/$ - see front matter
doi:10.1016/j.conengprac.2006.05.015

(Aweya & Montuno, 2001; Chait et al., 2001; Deb, Srikant, & Zhikui, 2003; Hollot et al., 2001, 2002; Low et al., 2002; Manfredi, di Bernardo, & Garofalo, 2004; Park, Lim, Basar, & Choi, 2004; Park, Lim, Park, & Choi, 2004; Rotkowitz & Lall, 2004; Quet & Ozbay, 2004; Sun, Ko, Chen, Chan, & Zukerman, 2003; Ying, Dullerud, & Srikant, 2004; Zhikui & Paganini, 2002). For example, to deal with the disadvantages of a classical RED controller, a proportional-integral (PI) controller is proposed in Hollot et al. (2002) to obtain zero steady-state error, better responsiveness and robustness (see Hollot et al., 2002 for further details). The controller is successful in achieving a better regulation of the queue length when compared with classical methods. Nevertheless, it performs poorly in the presence of network parameter variations such as RTT and load variations which are bound to occur in more realistic networks (Larry & Davie, 2000; Manfredi et al., 2004; Quet & Ozbay, 2004). Indeed in more realistic networks, the RTT can also vary with respect to its nominal value because of congestion phenomena and other effects such as the presence of responsive sources variations at different points in the network (causing the variation of equivalent RTT propagation delay), rerouting, additional unresponsive source traffic. Also the assumption of fixed long-lived TCP workload, often taken in the derivation of these models, is also violated in realistic network scenarios. This paper is concerned with the design of improved AQM control schemes taking into account explicitly the presence of RTT delay in the controller design and to cope with unwanted variations of characteristic parameters such as the RTT and load. In particular: (i) firstly a full state feedback controller is synthesized based on an appropriate robust reduction method for time-delays systems; (ii) a reduced robust observer for time delay systems is used in the control loop to avoid direct measurement of the transmission window, as this would be unpractical in applications; (iii) the resulting control law is validated and tested through numerical simulations both in Matlab/Simulink and network simulator (NS-2) (Fall & Varadhan, 2001), and is shown to exhibit improved margin stability and network performance in terms of a reduced number of packet losses, a more efficient queue utilization and better regulation, and shorter queuing delays.

2. A fluid model of TCP behavior

A fluid model of TCP dynamical behavior was derived in Misra et al. (2000) using the theory of stochastic differential equations. The model describes the evolution of the average characteristic variables on the network such as the average TCP window size and the average queue length. Extensive simulations in NS-2 have shown that the model captures indeed the qualitative behavior of TCP traffic flows. Hence, it is particularly useful for the design of innovative AQM control schemes for TCP-controlled flows using a control theory approach.

Under the assumption of neglecting the TCP timeout, the model is described by the following set of nonlinear coupled ODEs:

$$\dot W(t) = \frac{1}{R(t)} - \frac{W(t)}{2}\frac{W(t-R(t))}{R(t-R(t))}p(t-R(t)),$$
$$\dot q = \begin{cases} -C + \dfrac{N(t)}{R(t)}W(t), & q>0, \\ \max\left\{0, -C + \dfrac{N(t)}{R(t)}W(t)\right\}, & q=0, \end{cases} \tag{1}$$

where W is the average TCP window size (packets), q the average queue length (packets), T_p the propagation delay, R the transmission RTT ($R = q/C + T_p$), C the link capacity (packets/s), N the number of TCP sessions and p the probability of a packet being marked. All variables are assumed nonnegative. If we assume $N(t) = N_0$, $R(t) = R_0$ and $C = C_0$ to be the nominal values of R, N and C, then linearize the dynamic model (1) about the operating point (W_0, q_0, p_0) where W_0, q_0 are the state values of the equilibrium of interest when the input p is set equal to p_0 (see Hollot et al., 2001, 2002 for further details). Hence, in this case the following set of delay differential equations (DDEs) is obtained:

$$\delta\dot W(t) = -\frac{N_0}{R_0^2 C_0}(\delta W(t) + \delta W(t-R_0)) - \frac{R_0 C_0^2}{2N_0^2}\delta p(t-R_0),$$
$$\delta\dot q(t) = \frac{N_0}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t), \tag{2}$$

where $\delta W \doteq W - W_0$, $\delta q \doteq q - q_0$, $\delta p \doteq p - p_0$. In what follows it is considered $C_0 = 1875$ packets/s, $R_0 = 0.307$ s, $N_0 = 50$, $q_{max} = 400$ packets corresponding to the steady-state operating regime $W_0 = 11.5$ packets, $q_0 = 200$ packets, $p_0 = 0.0151$. As shown in Hollot et al. (2001), the delay R_0 in the state term $\delta W(t - R_0)$ in (2) can be neglected when $W_0 \gg 1$. This is a realistic assumption for a typical network operating condition and so for control design purposes the simplified model is considered:

$$\delta\dot W(t) = -\frac{2N_0}{R_0^2 C_0}\delta W(t) - \frac{R_0 C_0^2}{2N_0^2}\delta p(t-R_0),$$
$$\delta\dot q(t) = \frac{N_0}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t). \tag{3}$$

The AQM control strategy introduced in the paper is designed in the previous model. The robust nature of the strategy presented here will not only reduce the sensitivity to network parameters but also eliminate inaccuracies due to the use of the linear model (3).

3. Control design

As mentioned above, TCP models are typically characterized by the presence of time delays associated to RTT.

In what follows the design of an output feedback control scheme for AQM is carried out, which is robust to unwanted variations of parameter uncertainties such as