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GA-based PID active queue management control design for a class of TCP communication networks

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Abstract

Active queue management (AQM) is a key congestion control scheme for reducing packet loss and improving network utilization in TCP/IP networks. This paper proposes a proportional–integral-derivative (PID) controller as an active queue manager for Internet routers. Due to the limitations of packet-dropping probability and the effects of propagation delays in TCP networks, the TCP AQM network was modeled as a time-delayed system with a saturated input. An improved genetic algorithm is employed to derive optimal or near optimal PID controller gains such that a performance index of integrated-absolute error (IAE) is minimized, and thereby a stable queue length, low packet loss, and high link utilization for TCP networks are guaranteed. The performance of the proposed control scheme is evaluated in various network scenarios via a series of numerical simulations.

Keywords: AQM; TCP/IP; Congestion control; Genetic algorithm; PID controller

1. Introduction

Since the unpredictable interference and the number of users has grown rapidly in today's Internet environment, network traffic congestion results in long time delays for data transmission and frequently makes the queue length in the buffer of the intermediate router (switch) overflow, and can even lead to network collapse (Huang, Cheng, Chuang, & Jang, 2006; Kim et al., 2007). Therefore, a congestion control mechanism which determines a queuing guideline for the routers (switches) should be proposed to indicate the order in which packets are delivered and denote which packets should be dropped when congestion occurs. The active queue management (AQM) scheme is an efficient solution that detects inceptive congestion and gives early notice of conditions of the information for the current Internet situation by dropping (or marking) incoming packets before router queues become full.

The first well-known AQM scheme, random early detection (RED) (Floyd & Jacobson, 1993) algorithm, was developed and introduced into Internet routers for reducing the flow synchronization problem and clamed the traffic load via measurement of average queue length. Nevertheless, several studies and theoretical analyses have shown that the performance of RED is sensitive to its parameter settings and traffic load due to it being designed in an *ad hoc* architecture (Feng, Shin, Kandlur, & Saha, 2002). Therefore, a number of new modified schemes including ARED (Floyd, Gummadi, & Shenker, 2001), FRED (Lin & Morris, 1997), and SRED (Qtt, Lakshman, & Wong, 1999), have been proposed in the literature. However, those studies are unable to maintain the system performance in a wide range of operational conditions such as the number of connections, propagation delay, and link capacity.

A fluid-based model of the dynamics of the TCP and RED was developed by the stochastic theory (Misra, Gong, & Towsley, 2000). This model represents the behavior of the characteristic variables of the network and shows that it accurately captured the qualitative evolution of TCP traffic flows. Based on this TCP model, several congestion

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control schemes have been developed to improve the performance of communication networks (Ren, Lin, & Yin, 2005; Wang & Hollot, 2003; Yan, Gao, & Özbay, 2003; Zhang, Liu, & Dou, 2003).

On the other hand, based on the linearized fluid-based TCP/AQM model, a proportional–integral (PI) controller (Hollot, Misra, Towsley, & Gong, 2001) was developed to regulate the queue level, round-trip time, and packet loss. However, PI controller is sluggish with taking too long time to achieve the desired queue length due to PI controller improves the steady-state error at the cost of an increase in rise time (Bequette, 2003). Therefore, in order to overcome the drawbacks of PI controller, several new modified methods are proposed. The virtual rate control (VRC) algorithm for AQM in TCP networks has been proposed in Park, Lim, Park, and Choi (2004). In Ren, Lin and Wei (2005), a DC-AQM algorithm based on PID control was developed for large delay networks. A Smith predictor-based PI (SPPA) controller was presented to reduce the effects of the time delays in the control loop by a predictor (Li, Ko, & Chen, 2005). In the work of Wang, Wang, Zhou, and Huai (2006), the Particle Swarm optimization (PSO)-based PID controller was presented for an improved TCP/AQM with large-delay network situations. For improving the transient performance of the fixed-gain PI controller over a wide range of uncertainties, a stable queue-based adaptive proportional–integral (Q-SAPI) controller for AQM was proposed in Chang and Muppala (2006). However, the above researches are based on the linearized model and the complexity of the controller design, except for PID or PI controllers, is hard to realize. In addition, a saturated nonlinearity of the control input usually exists in this control problem due to the property of packet-dropping probability. Therefore, the effect of a saturated actuator should be considered; otherwise it can cause serious degradation and instability in a network with typically large-scale, complex systems. Accordingly, based on PID control, an efficient selection mechanism of the parameters for the PID controller with the property of input saturation, in this complex nonlinear model should be anticipated.

The Genetic algorithm (GA) has been considered as a useful technique employing the principles of natural genetic systems (Goldberg, 1989) to search a global solution of optimization problem. The basic idea is to maintain a population of possible solution that evolves and improves over time through a process of competition and controlled variation. It has been successfully applied in different areas such as modeling and classification (Setnes & Roubos, 2000), power quality assessment (El-Zonkoly, 2005), resource allocation (Wang & Lin, 2007) and, adaptive scheduling system (Juang, Lin, & Kao, 2007), etc.

In this paper, we develop a PID controller for a time-delayed TCP system with input saturation to ensure stable queue length, low packet loss, and high link utilization. Based on the improved GA search method, an efficient mechanism for selecting the controller gains of the PID controller is proposed. The proposed GA-based PID AQM scheme possesses a reliable stability and is robust against the number of TCP sessions, the various RTT, bursting and unresponsive flows, etc.

The rest of this research is organized as follows. Section 2 presents the TCP model and the control objective. An improved GA-based PID controller design for AQM is illustrated in Section 3. Section 4 shows the results of simulations to demonstrate the performance of the proposed control scheme. Finally, brief conclusions are provided in Section 5.

2. System description and problem formulation

A window-based nonlinear fluid-flow dynamic model for TCP networks is considered in this study. A detailed justification of this model was presented in Hollot et al. (2001) and Kelly (2001). Briefly, this model expresses the coupled non-linear differential equations such that they reflect the dynamics of TCP accurately with the average TCP window size and the average queue length. The coupled non-linear differential equations are given as follows:

$$\dot{w}(t) = \frac{1}{\frac{q(t)}{C} + T_p} - \frac{w(t)}{2}\frac{w(t-R(t))}{\frac{q(t-R(t))}{C} + T_p}p(t-R(t)) \tag{1.a}$$

$$\dot{q}(t) = \begin{cases} -C + \frac{N(t)}{\frac{q(t)}{C}+T_p}w(t) & \text{if } q(t) > 0 \\ \max\left\{0, -C + \frac{N(t)}{\frac{q(t)}{C}+T_p}w(t)\right\} & \text{if } q(t) = 0 \end{cases} \tag{1.b}$$

where w is the average TCP window size (in packets); q is the instantaneous queue length (in packets); T_p is the propagation delay (in seconds); R is the transmission RTT, equal to $q/C + T_p$; C is the link capacity (in packets/sec); N is the number of TCP connections; and p is the packet-dropping probability, which is the control input to decrease the sending rate and maintain the bottleneck queue length. All of the above variables are supposed to be nonnegative. In Eq. (1.a), the additive increase and multiplicative decrease (AIMD) congestion control algorithm is used to evaluate the average window size during the TCP flow, while Eq. (1.b) is the dynamics of the queue length accumulated as the transmission rate surpasses the link capacity.

Since the packet-dropping probability is between 0 and 1, the following nonlinear time-delayed system with a saturated input can be derived from Eq. (1):

$$\dot{w}(t) = \frac{1}{\frac{q(t)}{C} + T_p} - \frac{w(t)}{2}\frac{w(t-R(t))}{\frac{q(t-R(t))}{C} + T_p}\mathrm{sat}(u(t)) \tag{2.a}$$

$$\dot{q}(t) = \begin{cases} -C + \frac{N(t)}{\frac{q(t)}{C}+T_p}w(t) & \text{if } q(t) > 0 \\ \max\left\{0, -C + \frac{N(t)}{\frac{q(t)}{C}+T_p}w(t)\right\} & \text{if } q(t) = 0 \end{cases} \tag{2.b}$$

The saturated input $u(t) = p(t - R(t))$ is expressed by the following nonlinearity:

$$sat(u(t)) = \begin{cases} u_{\max}, & u(t) \geqslant u_{\max} \\ u(t), & u_{\min} \leqslant u(t) < u_{\max} \\ u_{\min}, & u(t) < u_{\min} \end{cases} \tag{3}$$