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A robust proportional controller for AQM based on optimized second-order system model ☆

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ABSTRACT

Active Queue Management (AQM) is an effective mechanism to improve the performance of end-to-end congestion control. However, existing AQM schemes are sensitive to network traffic changes. In this paper, we propose a novel AQM algorithm based, for the first time, on the optimized second-order system model, called Adaptive Optimized Proportional Controller (AOPC). AOPC measures the latest packet loss ratio, and uses it as a complement to queue length in order to dynamically adjust packet drop probability. Through using TCP throughput model, AOPC is capable of detaching from the number of TCP sessions N and insensitive to various network conditions. The parameter tuning rule is in compliance with the optimized second-order system model which has a small overshoot and fast convergence speed. We comprehensively evaluate the performances of AOPC through extensive simulations using NS2 simulator, and contrast it with previous approaches such as REM, PI, PID, PIP, and LRED. Simulation results demonstrate that AOPC is more responsive to time-varying network conditions than other algorithms, and obtains the best tradeoff between utilization and delay.

1. Introduction

Designing a scalable Active Queue Management (AQM) scheme to co-operate with TCP end-to-end congestion control has received much interest recently [1]. The TCP end-to-end congestion control scheme is effective in preventing congestion collapse, especially when most of the flows are responsive to packet loss in congested routers. Unresponsive flows, however, do not slow down their sending rates when the network becomes congested, and they indeed obtain more bandwidth, results in a longer time for the network to recover from congestion. Traditional end-to-end congestion control and drop-tail buffer management are insufficient to assure even minimal fairness, delay or loss guarantees, let alone providing quality of service support.

To mitigate such problems, AQM has been proposed at intermediate nodes to improve the end-to-end congestion control [1]. Generally, an Internet congestion control mechanism is comprised of two components. First, a flow control algorithm which runs in end hosts. During the congestion avoidance phase, TCP sources increase the congestion window size by one segment per round-trip time in the absence of congestion, and halve the congestion window size in response to a round-trip time with a congestion event, which is known as Additive Increase and Multiplicative Decrease (AIMD). Second, the link management algorithm executed in intermediate routers. Internet routers trigger the packet dropping (or marking, if Explicit Congestion Notification (ECN) [2] is enabled) in advance when the onset of congestion is perceived, which is the basic idea of AQM. The design objectives of AQM are as follows. (1) reducing packet loss ratio at routers; (2) providing high throughput and low end-to-end delay and jitter; (3) being stable and responsive under dynamic network scenario; (4) being simple, efficient and scalable to deploy.

In existing AQM schemes, link congestion is estimated through queue length [3], traffic input rate [8,9], packet loss ratio [11,18], buffer overflow and emptiness [7], or a combination of these congestion indicators [10,12]. Queue length (or average queue length) is widely used in RED [3] and most of its variants [4–6], where packet drop probability is often linearly proportional to the queue length. Many studies have demonstrated that the performance of RED is inherent deficient in parameter settings. Floyd, the designer of RED, and other researchers have made great efforts to provide guidelines in parameter settings, such as gentle-RED [4], ARED [5], SRED [6] etc. Although these schemes work more effectively than RED under a wide range of traffic scenario, the major drawback is that their queue lengths oscillate largely under special network load and traffic conditions, resulting in low throughput and high queueing delay. BLUE [7] adjusts the marking (or dropping) probability based upon the buffer overflow and link idle events. The traffic input rate is also used in some AQM schemes such as

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AVQ [8] to make the input rate match the link output rate. Many other schemes, such as REM [10] and RaQ [12], use both queue length and input rate to estimate congestion level. In [14], the fluid model of TCP behavior derived in [13] has been linearized by Hollot et al. and a second-order feedback control system was obtained thereafter. Subsequently, a Proportional-Integral (PI) controller [15] is designed to regulate the TCP/AQM interconnection system. The TCP/AQM interconnection system gives a framework for network researchers to design an AQM controller to regulate the system. Based on the system framework, Proportional-Integral-Derivative (PID) controller [16], PIP [17], and LRED [18], are proposed to eliminate the drawbacks in PI controller. These sophisticated controllers indeed enhance the performance in wide network scenarios; however, the connatural demerit of these controllers is that the control parameters are configured in particular network scenarios so that they lack of flexibility. The strong correlation between the control parameters and network parameters makes these controllers be prone to be unstable. The *stability* and *convergence* are two important issues which should be considered in the system design. Existing AQM controllers are sensitive to network load and obtain unsatisfactory stability and convergence under dynamic network environment, which motivate us to develop a robust controller with both stable control of queue evolution and fast convergence rate to the desire queue length under a variety of network scenarios.

The design is motivated by the following observation. The TCP throughput formula, which is derived from [19], can be useful in decoupling AQM design from the number of TCP sessions N. Based on the optimized second-order system model which has a small overshoot and fast convergence rate, together with the TCP throughput formula, we propose a robust AQM scheme, called Adaptive Optimized Proportional Controller (AOPC). AOPC periodically measures the packet loss ratio and uses it to compute a tuning factor of the control parameter. With this tuning factor, the AOPC tunes the control parameter adaptively, tracking the dynamic network load. Besides, AOPC applies the optimized second-order system model to ensure the satisfactory performance and guarantee the system stability. It has a better system closed-loop performance over the approaches tuned by the classical Ziegler–Nichols rule. Through extensive simulations under various network configurations, we show that, compared to existing AQM schemes, such as REM, PI, PID, PIP, and LRED, AOPC scheme offers more stable control of queue length around the desired queue length, thus achieves higher link utilization. AOPC also has better responsiveness and robustness.

The remainder of this paper is organized as follows. In Section 2, we review the control system models. Section 3 presents the AOPC scheme and gives some guidelines for parameter settings. A performance analysis is also presented at the end of this section. We compare AOPC with REM, PI, PID, PIP and LRED through NS simulation in Section 4. We conclude this work in Section 5.

2. Control system model

In this section, we introduce the TCP/AQM interconnection system model, the optimized second-order system model, and the general properties of proportional AQM control.

2.1. TCP/AQM Interconnection system model

Transient behavior of networks with AQM routers supporting TCP flows was described by a couple of nonlinear ordinary differential equations [13]. These equations are linearized in [14] and the linear TCP/AQM interconnection system is depicted in Fig. 1,

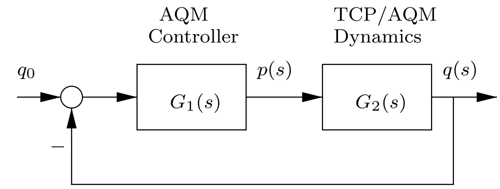

Fig. 1. Block diagram of TCP/AQM interconnection system.

where q_0 is the desired queue length, $G_1(s)$ is the AQM controller, $G_2(s)$ is the "plant" or TCP window-control and queue dynamics we try to control.

The objective of the AQM controller is to regulate the queue length to the desired value q_0 by marking (dropping) packets with a probability p as a function of measured queue length deviation between instantaneous and desired value. The transfer function of $G_2(s)$ is:

$$G_2(s) = \frac{K_m}{(T_1 s + 1)(T_2 s + 1)}, \tag{1}$$

where,

$$K_m = \frac{(RC)^3}{4N^2}, \quad T_1 = \frac{R^2 C}{2N}, \quad T_2 = R. \tag{2}$$

where, N is the number of active TCP sessions, R is the round trip time (RTT), and C is the link capacity.

By choosing different forms of $G_1(s)$ and employing different methods to determine the parameters of $G_1(s)$, we have different AQM algorithms (Controllers). The widely adopted controller is the general PID (Proportional-Integral-Differential) controller. Due to the modeling inaccuracies, as listed in [17], a parameter tuning structure is (1) to correct this simple plant or controlled object; and (2) insensitive to the drift of system parameters. In previous works, the control parameters of $G_1(s)$ are determined only based on some special network and traffic conditions. This paper proposes a self-tuning proportional controller that can determine the controller parameters dynamically.

2.2. Optimized second-order system model

Consider the closed-loop transfer function of the second-order system:

$$G(s) = \frac{K}{\tau^2 s^2 + 2\zeta\tau s + 1}, \tag{3}$$

where K is the static sensitivity, τ is the time constant, and ζ is the damping factor. The magnitude–frequency characteristic $A(\omega)$ and the phase–frequency characteristic $\varphi(\omega)$ are given by:

$$A(\omega) = \frac{K}{\sqrt{(1-\omega^2\tau^2)^2 + 4\zeta^2\omega^2\tau^2}},$$

$$\varphi(\omega) = -\arctan\frac{2\zeta\omega\tau}{1-\omega^2\tau^2}.$$

The damping factor ζ is vital to the performance of the second-order system [23]. When ζ is very small (close to zero) at $\omega\tau = 1$, the value of $A(\omega)$ is very large, which is called resonance. With the increasing of ζ, the resonance peak descends. When $\zeta \geqslant 0.707$, the resonance peak vanishes and $A(\omega)$ is a decreasing function of ω. In engineering, the second-order system is classified into under damping, critical damping, and over damping system corresponding to $\zeta < 1$, $\zeta = 1$, and $\zeta > 1$. The second-order system is optimal when $\zeta = 0.707$. For $0 < \zeta < 1$, the closed-loop poles are a pair of complex conjugates $-\frac{\zeta}{\tau} \pm j\frac{\sqrt{1-\zeta^2}}{\tau}$ in the left-half s-plane, and the step response of the second-order system described by (3) is