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ScienceDirect
Computer Communications 31 (2008) 1911–1918
computer communications
www.elsevier.com/locate/comcom

Design of a stabilizing AQM controller for large-delay networks based on internal model control ☆

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Received 29 March 2007; received in revised form 9 December 2007; accepted 17 December 2007
Available online 31 December 2007

Abstract

We focus on the problem of the stability of congestion control for networks with large round-trip communication delays. Nearly all the existing AQM schemes neglect the impact large communication delay has on system behavior, such as stability, robustness and convergence. The drastic queue oscillations in large delay networks of PI, REM and DC-AQM decrease link utilization and introduce avoidable delay jitter. To address this problem, we propose a robust IMC-PID congestion controller based on the internal model control principle to restrict the negative impact of the stability caused by large delay. Simulation results demonstrate that the integrated performance of our proposed scheme outperforms others as communication delay increases, and achieves high link utilization and small delay jitter.

Keywords: Congestion control; Active queue management; Internal model control; Large-delay networks; Stability

1. Introduction

Congestion control in communication networks has become increasingly important due to the explosive expansion and the growth of traffic. From the control theory point of view, congestion control problems are complex and challenging due to their high-dimensional, nonlinear, and dynamic properties. In practical, individual sources have to select their transmission rates in a decentralized way with little information about the rest of the network.

Recent advances in mathematical modeling of congestion control have stimulated the research on theoretic analysis of the behavior, such as stability, robustness and fairness, of currently developed Internet congestion control protocols as well as the design of new protocols with higher performance [2–6]. One of the most important factors in the design of congestion control is its asymptotic stability, which is the capacity of the system to avoid oscillations in the steady-state and to properly respond to external perturbations caused by the arrival/departure of flows, variation in feedback, and other transient effects. Stability proofs for distributed congestion control become progressively more complicated as feedback delays are taken into account. However, most existing congestion controllers, such as RED [1], REM [7], PI [9], AOPC [10] and so on, neglect the impact on performance caused by large round-trip communication delay. Although DC-AQM [11] set its goal to tackle the delay stability issue in large-delay networks, the employed parameter tuning method, padé approximation, results in the large mismatch between plant and model. Simulation results in Section 2 illustrate these

☆ This paper is an extended version of our previous paper appeared in ICC 2007. This work is supported by the National Natural Science Foundation of China (60673164), the Provincial Natural Science Foundation of Hunan (06JJ10009), the Specialized Research Fund for the Doctoral Program of Higher Education of China (20060533057), and the Program for New Century Excellent Talents in University (NCET-05-0683).
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doi:10.1016/j.comcom.2007.12.023

controllers result in dramatic oscillations in large delay networks, which decrease the utilization of the bottleneck link and introduce the avoidable delay jitter.

The objective of this research is to propose a stabilizing congestion control system that maintains both stability and ideal transient performance under arbitrary feedback delays, especially in large round-trip communication delay scenarios. The proportional-integral-differential (PID) controller is widely adopted to regulate the network router buffer's queue length. Some advanced PID controllers, designed using various methods like gain margin, phase margin [14], dominant pole placement [9], and linear quadratic regulators [15], are proposed to improve the stability and responsiveness of the TCP/AQM system. However, these proposals do not consider the delay stability issue [16,17]. Stability proofs for distributed congestion control become progressively more complicated as feedback delays are taken into account. We solve this problem by applying the principle of internal model compensation in control theory to restrict the negative impact on the queue stability caused by feedback delay. We call the new scheme IMC-PID congestion controller. Instead of using padé approximation to approximate the delay element [11], we apply the Taylor series expanding approach to reduce the plant/model mismatch. By choosing appropriate PID parameters, the IMC-PID controller can maintain stability with higher link utilization and smaller queue oscillation than that of other AQM controllers with arbitrary feedback delays.

The rest of the paper is organized as follows. In Section 2, we evaluate the negative impact of large delay on TCP/AQM system performance. Section 3 makes an overview of the TCP/AQM control system and internal model control (IMC) principle. In Section 4, we develop a robust, stable IMC-PID congestion controller for large-delay networks and give some guidelines for parameter settings. The performance of IMC-PID is compared with that of REM, PI, and DC-AQM in Section 5. Finally, we conclude our research in Section 6.

2. Effect of large delay on TCP/AQM system performance

The dynamics of congestion control may be abstracted as a control loop with feedback delay. A fundamental characteristic of such system is that it becomes unstable for some large feedback delays. A fundamental principle from control theory states that a controller must react as quickly as the dynamics of the controlled signal; otherwise the controller will always lag behind the controlled system and will be ineffective. In the context of current proposals for congestion control, the controller is an AQM scheme. Most previous AQM schemes [1,7,9,10], which configure the parameters in the small-delay network scenarios, do not consider the effect of large feedback delay on TCP/AQM system performance. These design approaches cause the system oscillation in large feedback delay networks. Table 1 shows the round trip delays to different overseas websites from the host at Central South University in China. We can see that the maximum average RTT is larger than 1 s. However, Internet measurements report that roughly 75–90% of flows have RTTs less than 200 ms [20] and the average RTT is distributed around 180 ms [21]. Therefore, the RTTs between two overseas websites are on an average larger than that of a majority network flows.

Table 1
RTT statistical values

URL	Minimum delay (ms)	Maximum delay (ms)	Average delay (ms)
www.ieee.org (61.200.81.134)	411	432	419
www.acm.org (63.118.7.16)	1101	1155	1131
www.yahoo.com (209.73.186.238)	347	355	352
www.mit.edu (18.7.22.83)	298	308	302

In order to investigate the performance of the existing typical AQM schemes, in particular, we select PI, REM and DC-AQM schemes to verify their stability in large delay networks. We conducted two sets of simulations under the dumbbell network topology scenario with average RTTs of 150 and 400 ms having uniformly distributed RTT ranges of [100, 200] ms and [200, 600] ms, respectively. In both cases, the buffer size is 300 packets, and the reference queue length is set to 150 packets in all

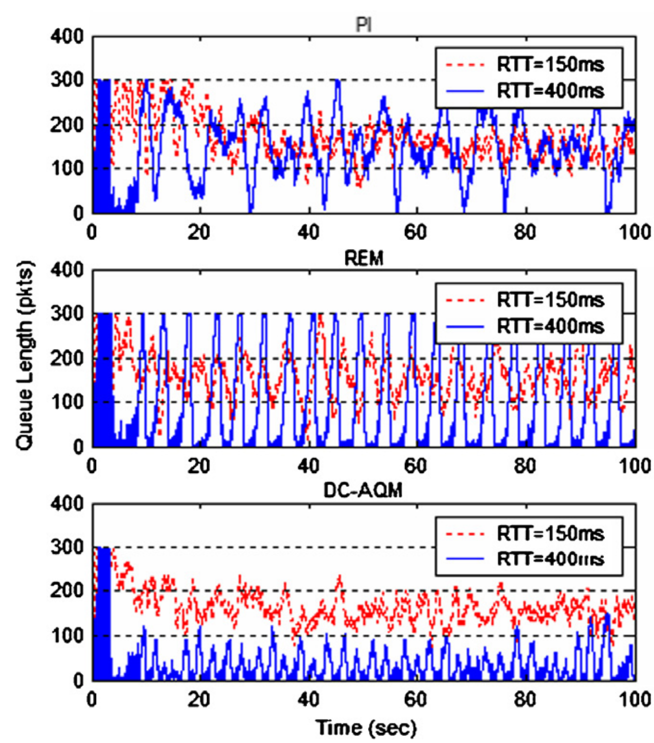

Fig. 1. Queue evolution. The dotted lines and solid lines represent RTT = 150 and 400 ms, respectively. All of the three AQM schemes are prone to being unstable while increasing RTT.