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Dynamic queue level control of TCP/RED systems in AQM routers

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ABSTRACT

One main TCP congestion control objective is, by dynamically adjusting the source window size according to the router queue level, to stabilize the buffer queue length at a given target, thereby achieving predictable queueing delay, reducing packet loss and maximizing link utilization. One difficulty therein is the TCP acknowledging actions will experience a time delay from the router to the source in a TCP system. In this paper, a time-delay control theory is applied to analyze the mechanism of packet-dropping at router and the window-updating in TCP source in TCP congestion control for a TCP/RED dynamic model. We then derive explicit conditions under which the TCP/RED system is asymptotically stable in terms of the instantaneous queue. We discuss the convergence of the buffer queue lengths in the routers. Our results suggest that, if the network parameters satisfy certain conditions, the TCP/RED system is stable and its queue length can converge to any target. We illustrate the theoretical results using *ns*2 simulations and demonstrate that the network can achieve good performance and converge to the arbitrary target queues.

1. Introduction

Internet congestion control and congestion avoidance have been active research interests in the area of networking (see, for example [1,3,7,11,12,14,16,17]) during the last two decades. It has two components: (1) the end-to-end congestion control protocol, such as TCP [15], and (2) an active queue management (AQM) scheme implemented in routers. AQM signals congestion by discarding or marking packets. When congestion is detected by TCP, it will take actions to reduce the source sending rate. Normally, AQM objectives are: to stabilize the buffer queue length at a given target, thereby achieving predictable queueing delay, and to minimize the occurrences of queue overflow and underflow, thus reducing packet loss and maximizing link utilization. Specially, random early detection (RED) [7] is a well-known queue-based AQM scheme, which introduces a control mechanism of the randomized packet dropping and a queue length averaging technique. RED's design objectives are to minimize packet loss and queuing delay, maintain high link utilization, and remove biases against bursty traffic. To realize these objectives, it is required [2,14] that RED stabilize the queue length at a given target so as to present predictable maximum queuing delay and to avoid the occurrences of queue overflowing and under-flowing, thus maximizing link utilization. However, the current version of RED is not successful in stabilizing the router queue. With related to the basic difficulty of stability, the proper selection of tuning parameters is a challenging issue. There are several tuning parameters in RED scheme, which are tightly coupled with each other. They need to be selected very carefully; otherwise the performance of RED will degenerate. The key requirement in selecting the appropriate parameters is the stability of the TCP/RED systems.

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In order to improve the performance of the basic RED [7] and its refined version [6], several efforts have been made such as [2–5,8,9,14]. Out of these publications, the notable works [9,14] discussed the stability issue of TCP/RED systems, in which the classical control system techniques like the standard frequency-domain analyzing methods are used to derive the local stability conditions for RED systems and the alternative AQM scheme (the proportional-integral control). Specifically, the results on the local stability of a single link with heterogeneous sources are proposed in [14]. The stability condition obtained in [9] relates the network parameters to the control feedback nature of the TCP/AQM model, such as the number of TCP sessions, link capacity and round-trip time. Further to the recent results reported in [17], in this paper, a time-delay control theory is applied to analyze the mechanism of packet-dropping at router and the window-updating in TCP source in TCP congestion control for a TCP/RED dynamic model. We derive explicit conditions under which the TCP/RED system is asymptotically stable in terms of the instantaneous queue. In order to discuss the convergence of the buffer queue in the router, we also derive the approximate solution of $q(t)$, by using the system model developed in [8]. Our results propose global stability and convergence conditions of the TCP/RED system but remove the limitations inherited in the known methods, by performing analyses of the TCP/RED system from the time-delayed control theory standpoint. The present work is different from that [17], in the way that we are now addressing the stability of instantaneous queue, and the convergence of dynamic queue. There is certain advantage in using instantaneous queue over using averaged queue, i.e., if congestion is detected by instantaneous queue, the possibility of buffer overflowing will be reduced. However, the stability of dynamic queue in a TCP/RED system has not been well addressed, so far. Of course, there is also disadvantage in using instantaneous queue compared to using the averaged queue, i.e., the TCP/RED system has a weaker robustness in dealing with bursty traffic.

We are able to employ the feedback control theory of time-delayed systems to enhance the performance of RED systems in a very logical manner due to the fact that, the overall operation of TCP/RED system (dropping packets on the basis of the queue level, sequenced acknowledgments, etc.) works [17] very similar to a time-delayed closed-loop control system. In this paper, control theoretic analyses are conducted on the basis of a TCP/RED dynamic model [8] by using the techniques [10,13] for constructing Hermite matrix for time-delayed control systems. We first establish explicit conditions under which the TCP/RED system is asymptotically stable in terms of the instantaneous queue length. We then discuss the convergence of the buffer queue length in the routers. Guidelines are then presented for designing RED controllers that can make the system stable and lead to the buffer queue's convergence to the arbitrary targets, subject to variations of network parameter (like number of active connections, round-trip delay and link capacity). Finally, we illustrate our results using *ns*2 [18] simulations and demonstrate that the network can achieve good performance and converge to the arbitrary target queues.

This paper is structured as follows. In Section 2, we analyze the feedback control system of TCP/RED to obtain its characteristic equation. Section 3 presents the main results on stability of the instantaneous queue length and the convergence of the buffer queue length. Section 4 is simulation verifications and finally in Section 5 we conclude the paper.

2. The feedback control system of TCP/RED

The recently developed TCP dynamic model [8] facilitates the application of time-delayed control principles to address the basic feedback nature of AQM. In this section, we first study the asymptotic stability of the TCP/RED system, in terms of the instantaneous queue length. Then we give the convergence analysis of the instantaneous queue length.

Consider an AQM based TCP/IP network having number of connections N, round-trip time R_0 and a single bottleneck transmission link of capacity C. In AQM schemes the data sender adjusts its congestion window size $W(t)$ after receiving congestion feedback signals about the queue length $q(t)$ from the bottleneck router. The following linearized fluid model [8] describes the dynamics of the congestion window size and the queue length at a given bottleneck router:

$$\begin{cases} \delta\dot{W}(t) = -\frac{2N}{R_0^2C}\delta W(t) - \frac{R_0C^2}{2N^2}\delta p(t-R_0), \\ \delta\dot{q}(t) = \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t), \end{cases} \tag{1}$$

where the component $\dot{x}(t)$ denotes the time-derivative of $x(t)$, the triple (W_0, q_0, p_0) is the equilibrium point of the system and $p(t)$ denotes the probability of packet dropping (or marking) which is specific to an AQM scheme like RED. In (1), we have also denoted

$$\begin{cases} \delta W(t) = W(t) - W_0, \\ \delta q(t) = q(t) - q_0, \\ \delta p(t) = p(t) - p_0. \end{cases} \tag{2}$$

With RED [7], a link maintains an exponentially weighted moving average (EWMA) queue length at the instance $t = n$,

$$avgq(n) = (1 - w_q)avgq(n-1) + w_q q(n), \tag{3}$$

where $avgq(n)$ denotes the averaged queue length and w_q is a weight parameter, $0 \leqslant w_q \leqslant 1$. When $avgq(n)$ is less than the minimum threshold ($\min_{th}$), no packets are dropped (or marked). When it exceeds the maximum threshold ($\max_{th}$), all incoming packets are dropped. When it is in between, a packet is dropped with a probability $p(n)$ that is an increasing function of $avgq(n)$. More specifically, if $\min_{th} \leqslant avgq(n) \leqslant \max_{th}$, then the temporary dropping (or marking) probability, $p(n)$, is calculated as