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Computer Networks 49 (2005) 580–592
Computer Networks
www.elsevier.com/locate/comnet

A nonlinear control theoretic analysis to TCP–RED system

Fengyuan Ren [a,*], Chuang Lin [a], Bo Wei [b]

[a] *Network Research Institute, Department of Computer Science and Technology, Tsinghua University, Beijing 100084, PR China*
[b] *Department of Electrical Engineering, Southern Methodist University, Dallas, TX 75275, USA*

Received 16 June 2004; received in revised form 27 December 2004; accepted 10 January 2005
Available online 21 March 2005

Responsible Editor: G. Morabito

Abstract

Random early detection (RED) is an effective congestion control mechanism acting on the intermediate node. The considerable recent studies have investigated on the stability of TCP/RED system. In this paper, we firstly summarize the contributions and limitations included in the existing works. To reveal a more comprehensive reason why TCP/RED system is apt to oscillate, a new analysis framework is constructed to sufficiently merge the existing valuable results with the aid of the describing function approach, which is rather mature in nonlinear control theory. After a brief introduction of the describing function approach, a proposition about TCP/RED system stability criterion is proposed. Subsequently, we use this criterion to quantitatively analyzed why gentle-RED is more stable than RED, and to investigate the impact of typical system parameters, such as propagation delay, load level, link capacity, and averaging weight factor, on TCP/RED system stability in detail. The simulation results validate our analysis.

Keywords: Stability; Limit cycle; Describing function; Active queue management

1. Introduction

Since Nagle [1] reported on the congestion collapse due to TCP connections unnecessarily retransmitting packets in 1984, the congestion control in IP networks has been a recurring problem. The end-to-end flow control mechanism invented by Jacobson forms the basis for TCP congestion control, and becomes mandatory requirements for all Internet hosts. Few would argue that the traditional TCP congestion control mechanism have served the Internet remarkably well and formed the basis for its survival and success, however, it is not sufficient to provide perfect performance in

* Corresponding author. Tel.: +86 10 62783596; fax: +86 10 62771138.
E-mail addresses: renfy@csnet1.cs.tsinghua.edu.cn (F. Ren), clin@csnet1.cs.tsinghua.edu.cn (C. Lin), bwei@engr.smu.edu (B. Wei).

1389-1286/$ - see front matter
doi:10.1016/j.comnet.2005.01.016

all circumstances, especially with the rapid growth in scale of network and the strong requirements to QoS support, because the corresponding algorithms merely focus on functions at the end-host, but the control which can be accomplished at end systems is limited. Accordingly, it is spontaneous to explore how to utilize the intermediate node ability to enhance the end-to-end congestion control. Following this consideration, ECN (explicit congestion notification) [2] and AQM (active queue management) [3] are successively developed. The goals of AQM aim at decreasing the end-to-end delay experienced by flows through maintaining the smaller queue in intermediate nodes, at the same time keeping the higher link utilization through avoiding the queue emptying. RED [4] was originally proposed to achieve fairness among sources with different burst attributes and to control the queue length to the expected range, which just meets the requirements of AQM, so RED algorithm was recommended as the only candidate algorithm for AQM in RFC2309 [3].

The basic idea of RED is to sense the coming congestion and try to inform the senders by either dropping or marking the packets. The dropping probability is updated according to the control law defined by a piecewise function of average queue length. This scheme includes four setting parameters: (1) $p_{\max}$, the maximum packet dropping probability, (2) w_q, the weighted factor, (3) $\min_{\text{th}}$, the minimum threshold of average queue length, (4) $\max_{\text{th}}$ the maximum threshold of average queue length.

RED is rather effective if correctly configured, however, many subsequent studies verified that RED is unstable and too sensitive to parameter configuration [5], and extremely hard to reduce the oscillation by tuning RED parameters [6], even more, some literatures discouraging implementation of RED (e.g. [7]) argued that there was insufficient consensus on how to select the values of the setting parameters because most of the rules for setting these parameters are empirical, and come from practical experience, and that RED could not be modified to provide a drastic improvement in performance. Therefore, some researchers began to explore why RED can induce network instability and major traffic disruption if not properly configured.

TCP/AQM oscillation may be caused by many factors, such as AIMD (additive increase multiplicative decrease) strategy employed by TCP flow control procedure, the noise-like traffic that are not effectively controlled by TCP (e.g. short lived TCP sessions), and non-responsive flows that are scarcely controlled by the sources (e.g. burst UDP traffic). However, more fundamentally, it is due to AQM algorithm itself. Many papers have theoretically analyzed TCP/RED system in framework of feedback control theory based on the continuous-time model (e.g. [8–12] etc.) or discrete-time model (such as [13] and [14]) after having made some necessary simplification and assumption, and finally provided some very revelatory and significant conclusions and judgments. In most of the existed works, the linear control theoretic approaches are frequently used. As for the complex nonlinear network system, they may not be the most appropriate choice, at least still have some limitations. In this study, we will apply the describing function (DF) approach, which is mature in nonlinear control theory, to analyze TCP/RED system, which is a typical nonlinear system since RED algorithm itself includes a structural nonlinear component, i.e. the piecewise control law. In our work, we will sufficiently take the existed results into consideration, and try to synthesize a stability criterion for TCP/RED system to more accurately and comprehensively reveal why TCP/RED is apt to oscillate. The remainder is organized as follows. In Section 2, the limitations in existing works are explained. In Section 3, the DF method and the stability criterion based on it are introduced in brief. In Section 4, a stability condition for TCP/RED system is deduced. Subsequently, we discuss the impact of typical network parameters on the stability, such as propagation delay, load level and link capacity, moreover do some simulations to support our analysis. Finally, a conclusion is drawn in Section 6.

2. Related works and their limitations

2.1. Analysis based on continuous-time model

Misra et al. developed a dynamic model of TCP behavior using fluid-flow and stochastic