ARTICLE IN PRESS

Engineering Science and Technology, an International Journal xxx (2016) xxx–xxx

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Design of feedback controller for TCP/AQM networks

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ARTICLE INFO

Article history:
Received 26 July 2016
Revised 10 September 2016
Accepted 3 October 2016
Available online xxxx

Keywords:
Active queue management
Congestion control
TCP/AQM
Control theory
Stability

ABSTRACT

In this paper, we propose a novel proportional-differential-type feedback controller called Novel-PD as new active queue management (AQM) to regulate the queue length with small oscillation. It measures the current queue length and uses the current queue length and differential error signals to adjust packet drop probability dynamically. We provide control theoretic analysis of system stability and develop guidelines to select control gain parameters of Novel-PD. The design of Novel-PD for TCP/AQM system is given in details. NS2 is used for conducting extensive simulation. The proposed controller is compared with random early detection (RED), random exponential marking (REM), proportional integrator (PI) and proportional derivative (PD) controller. Result shows that, Novel-PD is stable and achieves faster response in dynamic environments where number of TCP connections, bottleneck capacity, round trip time (RTT) keeps changing. The proposed controller outperforms other AQM schemes.

1. Introduction

Due to the tremendous growth of the Internet, traffic management has been an important factor in the network. In the last two decades the researchers pay more attention to find efficient means to control congestion for network with TCP/IP protocol. In recent years, active queue management (AQM) has been developed as router-based technique to mitigate 'TCP synchronization' problem [1] and to avoid congestion in the network. The objective of AQM is to signal congestion early before the buffer is full. It generates congestion signals as dual variable where a congestion measure is based on either packet loss or delay. Based on the received signal, the TCP can adopt source rate as primal variable. Due to this active behavior, the combined TCP/AQM system efficiently reduces congestion and overcome the synchronization problem with the proper selection of packet dropping/marking at every instant of congestion. The primary goal of AQM includes low queuing delay, high link utilization with lower packet loss. The other goals of AQM are to make the system stable and robust under different system parameters. AQM can be deployed at router to achieve high link utilization and low buffer occupancy. The high buffer occupancy may unnecessarily increase the queuing delay of packet and cause the timeout to occur frequently and leads to undesired retransmission. The undesired transmission further can cause low link utilization. For efficient queue utilization, the queue should avoid both underflow and overflow situation. One of the important functions of AQM is to measure incoming traffic rate and control the queue length where the nature of the traffic is bursty. Author in [2] proposed an AQM technique to predict change in packet arrival rate and uses the predicted value to define packet drop probability.

The motivation of this work is to design a new active queue management technique as a simple feedback controller to improve the performance of a network by stabilizing the queue length with small oscillation.

The rest of the paper is organized as follows. Section 2 provides related work and background details. Section 3 describes the dynamic model and section 4 presents the proposed algorithm. Section 5 provides the simulation setup to evaluate the performance of proposed controller and comparison with other existing scheme. Section 6 presents the simulation results.

2. Related work

AQM controllers can be classified into various categories such as queue-based, rate-based and both rate and queue-based [3]. Random early detection (RED) [4], Proportional Integral (PI) [5], Proportional Derivative (PD) [6] and Proportional Integral Derivative (PID) [7] are queue-based AQM controllers. Adaptive virtual queue (AVQ) [8], BLUE [9] and GREEN [10] are rate-based AQM controllers. Random Exponential Marking (REM) [11], RaQ

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Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2016.10.002
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[12], Virtual Rate Control (VRC) [13] and Yellow [14] are both rate and queue-based controllers. The heuristic approaches such as RED and its variants Adaptive RED (ARED) [15], Refined Adaptive RED (Re-ARED) [16], Nonlinear RED (NL-RED) [17], Stabilized RED (SRED) [18], Cautious Adaptive RED (CARED) [19], Loss-ratio based RED (LRED) [20], Exponential RED [21], Dynamic RED (DRED) [22], PD-RED [23] and FIF-RED [24] are designed to manage the queue efficiently.

RED and its variants require proper tuning of the parameters to get better performance. In those controllers the relation between system dynamics and controllers is not define clearly. To design an efficient controller for robust and stable operation, the TCP/AQM requires understanding of system dynamics. Various models have been proposed in the last decades to understand the dynamics of TCP/AQM system. The analytical model for TCP/AQM system is proposed in [25] and MGT fluid model is proposed in [5]. Later the fluid flow model is reviewed in [26] and proposed a non negative matrix method to model the dynamics of TCP system without considering any AQM controller. To optimize the control signal during each sampling period and to predict system dynamics, the Model Predict Control (MPC) [27,28] is designed.

Recently, much attention has been given to the stability and robustness analysis of AQM. To ensure stability of queue length, new AQM [29] is developed at the router and used control theory to overcome the nature of multiple delays. In [30], the stability of the AIMD/RED system is studied using multi-bottleneck topology and developed a mathematical model to analyze the stability of the system. Aoula et al. [31] proposed a fuzzy based AQM scheme based on queue length error and its change in error to enhance the robustness. To improve network congestion [32] the author proposed a new AQM which integrates RED and fuzzy PID approach. The applications of PD and PID controllers are not limited to AQM. It is applied in various fields of electrical engineering. The PD and PID controller can also be used to control the speed of brushless direct current drive [33] and for automatic voltage regulator [34]. Most of the industries prefer to use PID controller due to its simplicity. To improve the accuracy of the MGT fluid flow model under heavy TCP traffic a new analysis of TCP/AQM is provided in [35]. It shows a higher level of accuracy than previously designed MGT model and validated through NS2 simulation results. For heterogeneous system a state feedback controller [36] is designed maintaining closed-loop system stability through the Lyapunov-Krasovskii method.

The main contributions of this paper are as follows:

- We propose a new AQM algorithm as a feedback controller to regulate the queue length and achieve stability in the system supporting TCP flows. It measures the current queue length and uses it with differential queue errors to adjust packet drop probability.
- It applies control theory for system stability and provides a guideline to select control gain parameters of Novel-PD.
- Simulation experiment analysis of proposed algorithm is given in details. The proposed algorithm is compared with PD, RED, PI and REM.
- Novel-PD is stable under various scenarios, including multiple bottleneck links topology.

In this paper, a proportional-differential-type feedback controller is proposed to control congestion efficiently and achieve stability in the system. The proposed approach is simple and different from [23,37]. The proposed approach maintains more past history of the queue length error to make the system stable.

Proportional and derivative controller (PD) is developed based on queue length error and its change in error. The packet drop probability function of PD [6] is given in Eq. (1).

$$p(t) = p(t-1) + K_p \frac{(q_{avg}(t) - q_{ref})}{B} + K_d \frac{(q_{avg}(t) - q_{avg}(t-1))}{B} \qquad (1)$$

where K_p and K_d are the proportional and derivative gain respectively. $B$and q_{ref} are the buffer size and target queue length respectively. The first component is the ratio average error signal to the buffer size and second component is the ratio of differential average error signal to the buffer size. In this, the average queue length is used to calculate the average error signal.

In PD-RED, a proportional and derivative controller is added to RED algorithms. The packet drop probability function of PD-RED [23] is defined in Eq. (2).

$$max_p(t) = max_p(t-1) + K_p \frac{(q_{avg}(t) - q_{ref})}{B} + K_d \frac{(q_{avg}(t) - q_{avg}(t-1))}{B} \qquad (2)$$

It computes $max_p(t)$ for each sampling time and use it in RED as drop probability function. As in PD controller, PD-RED also uses the average queue length instead of current queue length to find error signal.

In NPD-RED [37], author proposed a novel self-tuning feedback controller to stabilize the instantaneous queue length. The packet drop probability of NPD-RED is defined in Eq. (3).

$$p(t) = p(t-1) + K_p \frac{(q(t) - q_{ref})}{B} + K_d \frac{(q(t) - q(t-1))}{B}. \qquad (3)$$

where $q(t)$ and $q(t-1)$ are the current queue length at time (t) and $(t-1)$ respectively. The first component is the ratio of current error signal to the buffer size and second component is the ratio of differential error signal to the buffer size. It considers current queue length to find error signal. In PD and PD-RED, the packet drop probability function considers average queue length error and differential average queue length error and buffer size. It only considers the current information to adopt the dropping probability. As it did not consider the past history, the presence of unresponsive traffic, short-lived traffic and multiple bottleneck links make the system unstable. Moreover, there is no theoretical analysis which defines the relation between control gain and system stability.

3. Dynamic model

For network flow dynamics, several theoretical models have been proposed in the literature. The TCP behavior was modeled in [25] using stochastic differential equation analysis. As specified in the model [25], a bottleneck network topology can be created where all the sources use TCP as their transport layer protocol as shown in Fig. 1. For simplicity, we assume the system is homogeneous where $W(t)$ is the TCP window size and $q(t)$ is the queue length in packets and $p(t)$ is the packet drop probability. Let $R(t)$ be the round-trip time of each TCP connection in second and C is the link capacity of single bottleneck link. Let T_p be the propagation delay, $r(t)$ be the incoming traffic rate and $N(t)$ be the number of TCP connections.

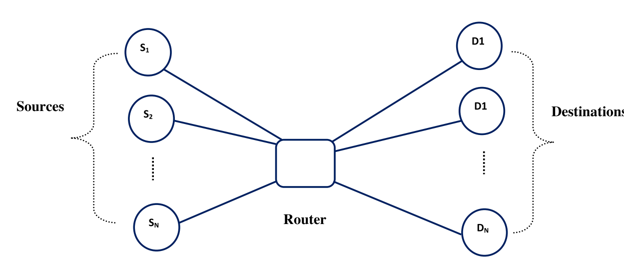

Fig. 1. Bottleneck Scenario.

Please cite this article in press as: S.K. Bisoy, P.K. Pattnaik, Design of feedback controller for TCP/AQM networks, Eng. Sci. Tech., Int. J. (2016), http://dx.doi.org/10.1016/j.jestch.2016.10.002