Control Engineering Practice 37 (2015) 67–79

Contents lists available at ScienceDirect

Control Engineering Practice

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

Stable Queue Management in communication networks

Sajjad Pourmohammad *, Afef Fekih, Dmitri Perkins

University of Louisiana at Lafayette, Lafayette, LA 70504, United States

ARTICLE INFO

Article history:
Received 14 August 2014
Accepted 3 January 2015
Available online 11 February 2015

Keywords:
Queue Management
Congestion control
Feedback control

ABSTRACT

Since Active Queue Management (AQM) was recommended by the Internet Engineering Task Force (IETF) as an efficient way to overcome performance limitations of Transmission Control Protocol (TCP), several studies have proven control theory to be a promising field for the design and analysis of congestion control in homogenous communication networks. AQM is gaining increased importance due to reports of buffer-induced latencies throughout the Internet. The increasing volume and diversity of traffic types (i.e., data, voice, and video) suggests that traffic management mechanisms, in general, and AQM schemes, specifically, must not only focus on the critical issue of congestion control but must also consider the QoS demands of heterogeneous traffic. However, to combine quality-of-service provisioning with congestion control, AQM design needs to be reconsidered. In this paper, we propose a state feedback controller design scheme for heterogeneous networks preserving the closed-loop system stability. Delay dependant stability conditions of the closed loop system are derived based on the Lyapunov-Krasovskii method. The proposed approach offers flexible choice of control parameters allowing the network administrator to control fairness and response time for each individual source node in a network of multiple links with different delay properties. The performance and robustness of the proposed controller were illustrated and analyzed using event-based computer simulations.

1. Introduction

Traffic management plays a significant role in the performance and reliability of data communication networks. Traditionally, congestion and flow control are the basic mechanisms used for traffic regulation within the Internet. Lack of proper congestion control mechanisms can lead to poor network performance and even congestion collapse (Jacobson, 1988). TCP's congestion control algorithms implement an end to end design which involves only the sender and receiver nodes. As networks grow larger, the packets travel through multiple intermediate routers and switches before arriving at the destination. Internet middle-boxes utilize store and forward mechanisms in which the packets are stored in an output link buffer and are forwarded when the bandwidth of the link is available. If the buffer reaches its full capacity, then the extra packets will be dropped (drop-tail mechanism). TCP's congestion control mechanism reacts to packet losses by decreasing the congestion window (and as a result the transmission rate). The drop tail approach, however, has many drawbacks such as large oscillations of the queue length, resulting in variations in delay, jitter, and unfair bandwidth allocation due to resource domination by aggressive and misbehaving flows (Adams, 2013). Active Queue Management (AQM) has been recommended by the Internet Engineering Task Force (IETF) as an efficient way to overcome performance limitations of Transmission Control Protocol (TCP) (Jacobson et al., 1998). AQM routers continuously monitor the network's state and inform the senders about any possible upcoming congestion.

Random Early Detection (RED) (Floyd & Jacobson, 1993) and its variants (e.g. Stabilized-RED (Ott, Lakshman, & Wong, 1999), Adaptive RED (Floyd, Ramakrishna, & Scott, 2001), Nonlinear RED (Zhou, Yeung, & Li, 2006)) and other algorithms like BLUE (Feng et al., 2002), BLACK (Chatranon, Labrador, & Banerjee, 2003), YELLOW (Long, Zhao, Guan, & Yang, 2005) are among the proposed AQM methods. RED as well as the AQM methods mentioned above are mainly heuristic approaches. Since the exact relation between the controller and systems dynamics is not clearly formulated, tuning controller parameters are often done based on intuition or trial-and-error methods. The difficulty of tuning the controllers' parameters is the main limitation for heuristic AQM approaches, which has hindered global deployment of AQM schemes (Adams, 2013) The "Bufferbloat" project (Bufferbloat, 2012; Gettys, 2011) has recently brought more awareness to AQM. It discusses how common it is to

* Corresponding author.
E-mail addresses: sxp7579@louisiana.edu (S. Pourmohammad), afef.fekih@louisiana.edu (A. Fekih), perkins@louisiana.edu (D. Perkins).

http://dx.doi.org/10.1016/j.conengprac.2015.01.001

experience delays in the network which are caused by poor buffer management. Delays in the order of few seconds are reported in some applications including ADSL broadband modems, DOCSIS cable modems, and last-hop routers (Nicholas & Jacbson, 2012). Since most popular loss-based TCP congestion control mechanisms (e.g., Reno) tend to aggressively fill any buffer; over-buffered devices can therefore lead to poor Internet performance (i.e., as perceived by the end users), specifically for delay-sensitive applications such as real-time interactive multimedia, Voice over IP, online gaming and even web browsing. This is especially apparent when sessions share the bottleneck queue with long-lived TCP connections. Recent studies showed that this issue is even more serious for devices with larger buffer capacities (Nicholas & Jacobson, 2012; Gong et al., 2014).

In this paper, a more rigorous and accurate AQM is proposed based on control theory to overcome some of the problems induced by over-buffering in the intermediate network devices. Control-theoretic approaches have been utilized before for the design of AQMs. A Proportional–Integral (PI) controller was designed in Hollot, Misra, and Towsley (2002) based on the TCP fluid-flow model introduced in Misra, Gong, and Towsley (2000). Employing classical PID controller design paradigms, a Pro-Active Queue Management (PAQM) was proposed in Ryu and Rump (2002). Robust control (Zheng & John, 2009; Chen & Yang, 2007; Quet & Ozbay, 2004), state feedback approaches (Kim, 2006; Ariba, Gouaisbaut, & Labit, 2009; Pourmohammad, Fekih, & Perkins, 2013), soft computing methods (Fatta, 2003; Fengyuan, Yong, & Xiuming, 2002; Yan, Kuo, & Liao, 2009; Moghaddam, 2010) and PD-RED (Han,Hollot, Chait, & Misra, 2004; Sun, Ko, Chen & Chan, 2003) are among the other control theoretic approaches that were considered for designing AQM routers. A recently published survey paper on AQM methods can provide further details about some of the considered approaches (Adams, 2013).

The main contributions of this paper are as follows:

- It successfully applies advanced control design to AQM in Active Queue Management in heterogeneous links with distinct time-varying delays.
- The proposed approach utilizes full state feedback making good use of QoS metrics in designing the controller for the desired queuing delay and resource allocation between different sources.
- The proposed controller is robust and preserves fairness.
- This work is the first to explicitly derive delay dependant stability conditions of the closed loop system based on the Lyapunov–Krasovskii method.

There are several factors that differentiate the work presented in this paper from existing works in the literature. Only a limited number of research works have addressed AQM design for heterogeneous network topologies (e.g., different link delay properties). In a simple bottleneck scenario, in which multiple sources are connected to a router, link properties such as delay and bandwidth can be different for each link. Considering AQM design for heterogeneous topologies makes the controller design more challenging but it offers a more accurate and realistic controller. Stability analysis of the controller is lacking in most of the papers and only computer simulations are used to show the system's stable operation. (Tang, Wei, Low, Chiang, 2009) In Kim (2006) the stability analysis of the employed state space approach was extended to heterogeneous links. However, the author did not provide any numerical results to illustrate the performance of the proposed method. A graphical stability criterion is proposed in Han et al. (2004) for AQM designs in heterogeneous network topologies invoking Generalized Nyquist Stability Criterion, which makes it inefficient for practical implementations when the number of nodes in the network increases (Toker & Özbay, 1996). In this paper, stability conditions of the closed loop system are derived using the Lyapunov–Krasovskii method in terms of Linear Matrix Inequalities (LMI) which makes it appropriate to use the projective numerical solvers to check the feasibility of the solution (Nemirovskii & Gahinet, 1994). Nowadays AQM's design focus has shifted from congestion control to the more general concept of quality-of-service (QoS). The main goal of the latter is to have the network simultaneously and efficiently serve the diverse requirements of the different types of traffic flows. In this context, the role of AQM is to serve as a mechanism for providing a better service, which can include different metrics and priorities depending on the type of network and service. Fairness, bandwidth allocation and congestion control for the smooth high performance operation of the network fit into this context. In this paper, a full state feedback approach is proposed for designing the controller, providing the flexibility needed for integrating all QoS requirements into the controller design.

The rest of the paper is organized as follows. Section 2 describes the network topology and the TCP fluid-flow model. The proposed control approach is developed in Section 3. Computer experiments summarizing the results from packet-level simulations are illustrated in Section 4. Finally, some concluding remarks are given in Section 5.

2. Dynamical model

Several mathematical models of network flow dynamics have been proposed in the literature (Misra et al., 2000; Hollot et al., 2002; Kelly, 2001; Misra, Wei-Bo, & Towsley, 1999). They are mainly focused on homogeneous topologies assuming the same delay properties for all the links connected to the router. In this paper we use the model proposed in (Low, Paganini, & Doyle, 2002) which extends the flow dynamics to heterogeneous topologies in which multiple links with different delay properties are considered.

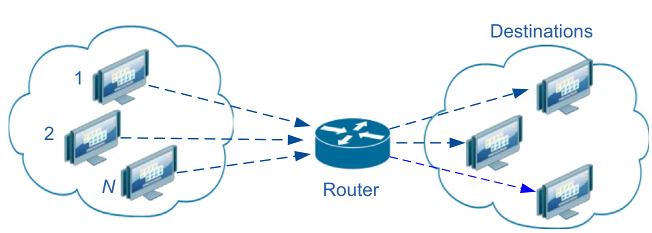

Fig. 1. Network configuration.