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Queue Management using Optimal Margin method to Improve Bottleneck Link Performance

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ABSTRACT

In network routers, buffers are used to resolve congestion and reduce packet loss rate whenever congestion occurs at bottleneck link. Most of the existing methods to manage such buffers focus only on queue-length-based control as one loop which have some issues of low link utilization and system stability. In this paper, we propose a novel framework which exploits two-loop control method, e.g. queue-length and congestion window size, combined with optimal margin method to facilitate parameter choices. Simulation results in ns-2 demonstrate that bottleneck link performance can be improved with higher link utilization (85%) and shorter queue length (22%) than the current deployed scheme in commercial routers (RED and DropTail).

Key words: AQM, Optimal Margin, Cascade Control, Fluid Flow.

1. INTRODUCTION

Computer networks are becoming more complex than ever and we still rely on them to transport data across globe in seconds. Although it works well, there are some foreseen issues need to be addressed. Firstly, interrupted connectivity problem has become more common because bandwidth-consumed applications such as peer-to-peer or video streaming are more popular. Moreover, bottleneck link performance is degraded seriously due to bad interaction between transport protocols at transport layer and queue scheduling at link layer. Some recent articles put forward the case for renewed research in the development of queue management policies for the Internet [1,2]. The authors in [2] have stated that "Unmanaged buffers are more critical today since buffer sizes are larger, delay-sensitive applications are more prevalent, and large (video streaming) downloads are common." The continued existence of large delays at bottleneck link could readily impact the growth of new applications, which makes a strong case for further analysis and design of active queue management (AQM) policies.

To compensate bad performance of bottleneck link due to large buffer existence in Internet equipments, AQM algorithms has been recommended to set up with new devices [3]. Most of AQM designs exploit the classical control theory and fluid-flow model to consider additive increase - multiplicative decrease (AIMD) feature of transport control protocol TCP (e.g., TCP Reno, Newreno, Sack, etc.) and bottleneck queue evolution through time. Some of the promising proposals for AQMs are drop-tail, random early detection (RED) [4], and CoDel [2] as a few recent proposals. However, none of these are currently implemented, and the drop-tail policy

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continues to be widely used in Internet routers due to its simplicity - but drop-tail also has implicit issues such as long queue if buffer size is large, which results into high latency and affects to user-experience with delay-sensitive applications (e.g., web browsing, video conference, etc.)

Leading from the prior works, in this paper, we propose an AQM design from control theoretical aspect, but using optimal margin method to choose the best coefficients of controllers. We realize that the existing models of AQM in control theory heavily concentrated on one-loop control to track the queue length reference, which have issues of difficult to adjust parameters and guarantee stability. By adding more loop to control congestion window size, we should improve the total bottleneck link performance in term of packet loss, link utilization and average queue length. The optimal margin method for our proposed active queue management scheme (AQM-MO) is used at both loops to make decision on sampling time and coefficients of inner and outer controllers. Our main contributions can be summarized as following:

- We propose an active queue management scheme using optimal margin (AQM-MO) in frequency domain which has two loops for control. The first loop gets information from congestion window size and bottleneck link capacity while the second one maintains queue length as desired value. An interesting result is that we can obtain close-form expressions to derive coefficients of controller easily (Section IV).
- We develop a simulation model to verify our proposal AQM-MO using ns-2. The proposed scheme is added at the same level to other existing schemes in ns-2 code (DropTail and RED). Simulation results are also provided with bottleneck link statistics: packet drop rate, queue length and link utilization (Section V).

The remainder of this paper is organized as follows. We present related works in section II. In section III and IV, we describe the system model and the dynamic feedback controller design specific steps. Section V gives our simulation results of the proposed scheme and section VI finally concludes the paper.

2. RELATED WORKS

Several models and algorithms have been proposed using control theoretic with the core linearized TCP model by Hollot et al. [5] which contributed a large portion to de-bloat research field [6]. The purpose firstly was to support more concrete design for RED parameters and an insight knowledge about its behavior under changing of network conditions such as propagation delay, offered load such as number of TCP flows and bottleneck link capacities. Here we make the classification into two main approaches: classical control and robust control.

From classical methods, proportional-integral-derivative (PID) controller-based algorithms have been designed to meet various requirements of bottleneck link in the Internet. Hollot et al. [5] interpreted RED as I-controller and proposed two variants of RED, the proportional (P) controller. and the proportional integral (PI) controller to improve RED. The stable region of control gains is determined for dynamic-RED (DRED) using Routh stability test in [7] with load-dependent probability to randomly discard packets whenever the buffer at bottleneck link grows excessively. The advantage of classical methods is that we can maintain queue size close to a pre-determined threshold value and do not have to collect state information of individual data flows. Nevertheless, most of the existing methods in classical control for AQM only use one-loop feedback of queue length.

Robust control method was also used to study AQM and bottleneck link performance. In [8], the issue of large delay was addressed by DC-AQM algorithm based on internal mode compensation (IMC) principle. Using the derived IMC controller, they tried to tune the coefficient controller K_p, K_i, K_d

to reduce end-to-end packet delay. Continuing to contend with large delay, a Gain Adaptive Smith Predictor with PI controller (GAS-PI) in [9] was proposed to gain more robustness of the TCP/AQM system. Then in [10], a predictive PID controller was proposed to determine suitable values for controller coefficients so that they can adapt with changes of offered load, round-trip time, etc. Recently, authors in [11] proposed a globally optimal solution using network optimization framework to resolve contention of packets under fast-fading wireless ad-hoc network environments.

During recent years, main directions has been transferred to more and more sophisticated robust control techniques, based on classical models (fluid-flow model of TCP/AQM) or queuing models with impatient customer feature [12]. Contributing to this research trend, we propose a two-loop control using optimal margin method which has not been considered in literature of AQM research field yet. Though this method can implicitly be a little bit complex with two additional controllers, we are going to demonstrate that the performance is much better in terms of packet loss and more link utilization than implemented schemes such as DropTail and RED.

3. SYSTEM MODEL

3.1 The classic fluid-flow model for TCP/AQM interaction

The TCP/AQM fluid-flow model described by nonlinear differential equations has been used to study interaction between TCP transport protocols and AQM schemes [5,8,10,13]. This model can capture the additive increase multiplicative decrease (AIMD) feature from TCP (Fig. 1) and queue length evolution from AQM, without slow start and time-out mechanisms [14]. However, this lacking affects initial start-up of the system only, once the system reach stable point, the differential equations solver can track changes in the network.

In detail, this model is firstly used for TCP Reno for intermediate and small buffers operating a DropTail queue policy. In TCP Reno, the congestion window size $w(t)$ at time t increases by one packet per acknowledgement, and decreases by half per packet drop. The rate at which packets are emitted at time t is approximately $\frac{w(t)}{R(t)}$, so the rate at which acknowledgements or loss indications are received at time t is $\frac{w(t-\tau)}{R(t-\tau)}$. Let $p(t)$ be the packet drop probability which is decided by AQM scheme. The fluid model for congestion avoidance phase of AIMD of TCP Reno is [15]:

$$\frac{dw(t)}{dt}=\frac{1}{R(t)}-\frac{w(t)}{2}\left[\frac{w(t-\tau)}{R(t-\tau)}\right]p(t-\tau)$$

Note: this is an approximation model of TCP/AQM network at bottleneck link only. However, it is still a good approximation when compared to packet-level simulation software, because there are enough flows in the network to saturate bottleneck link so that we can neglect aspects like time-out, slow start, fast recovery of different TCP

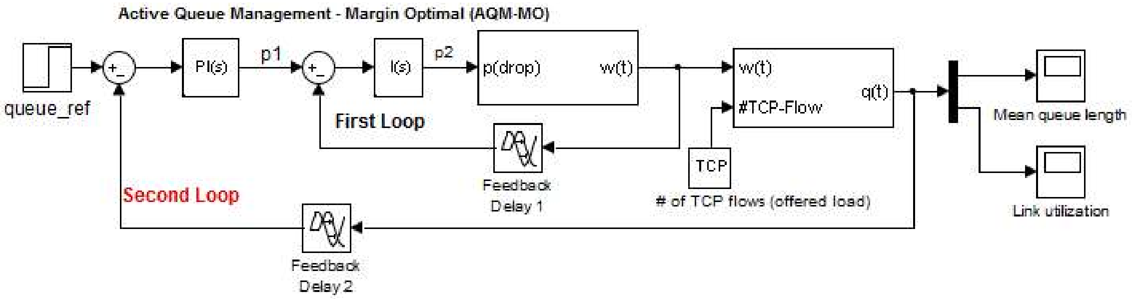

Fig. 1. Active queue management using optimal margin model (AQM-MO).

variants.

3.2 Self-similar bursty traffic generator model

In order to generate traffic to bottleneck link, we consider the following self-similar burst traffic generation model. This model is implemented based on the on-off period of Pareto distribution. One of the important requirements for the simulation experiment is to model the network traffic as close to reality as possible. At the moment, our networks usually experience bursty traffic or self-similarity which is a main characteristic of Internet traffic now and future [16]. It has been shown in the literature that self-similar traffic can be generated by multiplexing multiple sources of Pareto-distributed *on-off* periods. In this context, *on* periods correspond to a series of bursts sent one after another, and *off* periods are periods of silence. The more details can be seen on [17]. Here we summarized the most important result that we will use for our simulation model development later.

$$b_{off} = \left(\frac{1}{L} - 1\right)\frac{\alpha_{on}\alpha_{off} - 1}{(\alpha_{on} - 1)\alpha_{off}} b_{on}. \tag{1}$$

During the on period of the on-off source, bursts are sent back to back. L is average load of each on-off source. α is shape parameter, b is the distribution of on-off periods. Equation (1) is used to support the implemented code of the self-similar traffic generator module in our simulator.

4. ACTIVE QUEUE MANAGEMENT USING OPTIMAL MARGIN (AQM-MO)

4.1 The transfer function of bottleneck link

We follow the fluid-flow approach to model the congested bottleneck link in network router as:

$$\begin{aligned} \dot{w}(t) &= \frac{1}{R(t)} - \frac{w(t)w(t-\tau)p(t-\tau)}{2R(t-\tau)}, \\ \dot{q}(t) &= \frac{Nw(t)}{R(t)} - C_{btnk}, \end{aligned} \tag{2}$$

where C_{btnk} is the bottleneck link capacity (Mbps), R is the round trip time (seconds), N is number of TCP flows (offered load) and τ is the round-trip time propagation delay (since congestion happens until a sender knows via receiving explicit congestion notification (ECN) bits).

The stable operating point of model (2) can be derived by setting $\dot{w} = 0$ and $\dot{q} = 0$. Then we obtain:

$$\begin{aligned} w_0^2 p_0 &= 2, \\ w_0 &= \frac{R_0 C_{btnk}}{N}, \\ R_0 &= R_p + \frac{q_0}{C_{btnk}}. \end{aligned}$$

Doing linearizing around operating point (w_0, q_0, p_0) and using small signal model in control theory, we can get the TCP/AQM transfer function in Laplace domain which model the bottleneck link as follows:

$$\begin{aligned} Tr(s) &= Tr_{cwnd}(s).Tr_q(s).e^{-sR_0} = \left(\frac{w(s)}{p(s)}\right).\left(\frac{q(s)}{w(s)}\right).e^{-sR_0} \\ &= \left(\frac{A}{s+B}\right)\left(\frac{C}{s+D}\right).e^{-sR_0}, \end{aligned} \tag{3}$$

where $A = \frac{R_0 C_{btnk}^2}{2N^2}; B = \frac{2N}{R_0^2 C_{btnk}}; C = \frac{N}{R_0}; D = \frac{1}{R_0}.$

4.2 Designing controllers using optimal margin method

Two controllers for two loops are designed using optimal margin method in control theory. The main transfer function (3) is then decomposed into two parts for designing purpose. The first one controls dropping probability p_2 based on traffic information while the second one controls dropping probability p_1 based on the difference between measured average queue length and reference signal (Fig. 1).

First loop: the requirement for this loop is fast response to input changes. From [18], the objective function for this loop can be represented by a linear first-order function: $Tr_{cwnd}(s) = \frac{k_I}{1+T.s}$; where $k_i = A/B$ and $T = 1/B$ are integrator coefficient and sampling time interval, respectively. The close-loop transfer function of the first loop follows:

$$I(s) = \frac{w(s)}{p_1(s)} = \frac{Tr_{cwnd}(s)C_{first}(s)}{1+Tr_{cwnd}(s)C_{first}(s)}. \qquad (4)$$

To satisfy the system quality of (4), the output should be nearly same to the input signal. In the other words, the controller $C_{first} = \frac{1}{T_{first}s}$ should make the image in frequency domain $|I(jw)| = 1, \forall w$. This is called *optimal margin* method in control theory. However, due to several practical reasons (disturbance, noises, complex systems. etc.), this requirement is rarely satisfied for all frequencies w. An acceptable design is that $|I(jw)| \approx 1$ in a wide band of low frequencies as possible. We do experiment and then propose the sampling time interval of C_{first} such that $T_{first}^2 = 2k_i T_{first} T$. This heuristic of close-form expression of T_{first} can be used to make decision for design the first loop control.

Second loop: the second loop design can be approached in the same way. We have the closed-loop transfer function of the second loop as equation (5).

$$O(s) = \frac{q(s)}{q_{ref}(s)} = \frac{I(s)Tr_q(s)C_{\mathrm{second}}(s)}{1+I(s)Tr_q(s)C_{\mathrm{second}}(s)}. \qquad (5)$$

The difference from the first loop is that the objective function here is a linear third-order type, due to include of $I(s)$. Hence, we should choose a proportional-integral-derivative PID controller, and by using *optimal margin*, $|O(jw)| \approx 1$. Then the controller of the second loop is derived as following:

$$C_q(s) = k_{p_O}\left(1 + \frac{1}{T_{i_O}s} + T_{d_O}s\right),$$

where $k_{p_O}, T_{i_O}, T_{d_O}$ are PID coefficients and calculated using *optimal margin* method.

5. SIMULATION RESULTS

5.1 Simulation setup

We develop a simulation model to verify the performance of the proposed AQM-MO scheme using a popular discrete event network simulator ns-2 [19]. The chosen topology in Fig. 2 is a dumb-bell network which has been recommend to evaluating any queue management scheme [20]. Each client sends data at a constant rate to dedicated servers through n intermediate routers. To create an artificial bottleneck, we should set up the bottleneck link bandwidth as "high-to-slow", i.e., the bandwidth of links from clients to router 1 are high and the bandwidth of the bottleneck link between router is slow.

5.2 Simulation results and compared with other approaches

In this section, we analyze our simulation results which are obtained by randomly repeating experiments to know the effects of round-trip time (RTT) propagation of bottleneck link on network performance. Bottleneck link RTT is important for multiple reasons: it allows network operators and

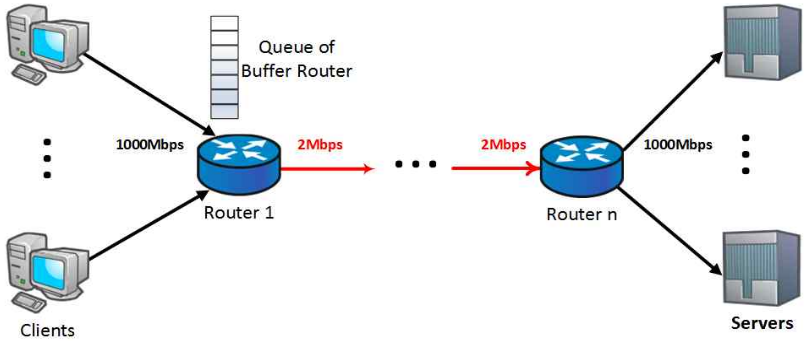

Fig. 2. Dumb-bell network topology with multi-bottlenecks.

end users to understand their network performance and help optimize their environment, and it helps businesses understand the responsiveness of their services to sections of their user base. Follow this direction, we choose a discrete set of RTT values, plotted in log scale, to run several experiments in ns-2 on evaluating three AQM schemes: DropTail, RED and our proposed AQM-MO using optimal margin method. Maximum value of RTT is 1000 (ms) which means that a packet can experience longer in bottleneck queue until it can emit congestion signal to transport protocol (i.e., TCP Reno). Hereafter, we show three performance criteria results which is important to evaluate TCP/AQM performance on bottleneck link: packet drop rate, queue length and link utilization. Some discussions on the trade-off between different criteria are also provided to interested readers.

At the first glance, from Fig. 3, we can see AQM-MO achieves the lowest packet drop rate versus different RTT values. Higher the RTT is, lower the packet drop rate is; and this is suitable to common operation of TCP/AQM interaction in network. Using optimal margin method to design AQM, we can reduce a few packet drop compared to existing scheme in Internet routers (−0.3% versus RED, −1% versus DropTail).

Secondly. mean queue length results are presented in Fig. 4. We can easily realize that there is a similarity between packet drop rate and mean queue length of AQM-MO. The queue becomes shorter than the other disciplines. With maximum queue size is 100 packets, the queue length of AQM-MO is ao Note that if RTT is over 30(ms), DropTail seems to be lock-out and saturate link; queue length of DropTail happens to be excessively grow than RED and AQM-MO. This interesting result confirms that DropTail has a problem of adaption to different network environments which motivates us to consider active queue management implementation in realistic.

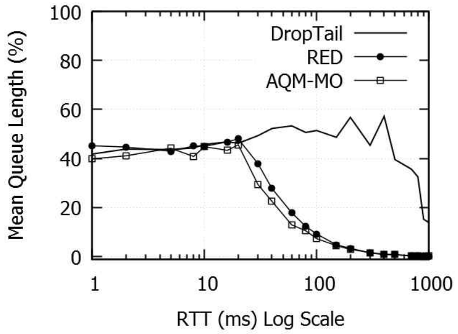

Fig. 4. Percent of Mean Queue Length with RTT Changes.

Finally, we show the bottleneck link utilization in percent for different RTT values in log scale measurement (Fig. 5). In fact, higher link utilization means the link busy, but lower link utilization also means that we do not use the resource (bandwidth) efficiently. Looking into our result in Fig. 5, we can see AQM-MO deal with this trade-off pretty well. The link utilization from AQM-MO is a little bit higher than RED algorithm, but much lower than DropTail. Therefore, if we implement

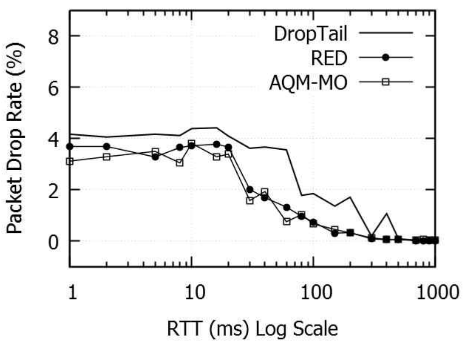

Fig. 3. Packet Drop Rate with RTT changes.

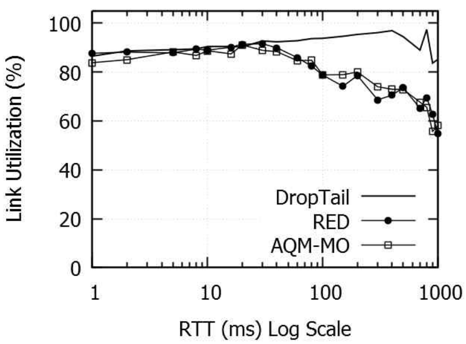

Fig. 5. Link Utilization with RTT Changes.

AQM-MO in Internet devices,

6. CONCLUSION

This paper proposes a novel active queue management scheme to improve bottleneck link performance in Internet routers due to large buffer issue. Optimal margin technique in control theory as AQM-MO is used to achieve the goal. A close-form expression to derive coefficients for controllers is then obtained through our proposal AQM-MO. Simulations using dumb-bell network topology in ns-2 demonstrate the efficiency of AQM-MO in terms of trade-off between lower packet loss rate and higher link utilization than existing schemes.

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