LRC-RED: A Self-tuning Robust and Adaptive AQM Scheme

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Abstract

In this paper, we propose a novel active queue management (AQM) scheme based on the Random Early Detection (RED) of the loss ratio and the total sending rate control, called LRC-RED, to regulate the queue length with small variation and to achieve high utilization with small packet loss. This scheme measures the latest packet loss ratio, and uses it and the total sending rate as complements to queue length in order to dynamically adjust packet drop probability. Further, we also provide the design rules for this scheme based on the well-known TCP control model. On the basis of the design rules, we develop a simple, scalable and systematic rule for tuning the control parameters which can be adaptive to dynamic network conditions. Through ns 2 simulations, we show the faster response time and better robustness of the proposed LRC-RED as compared with the Loss Ratio based RED (LRED) [5] algorithm.

1. Introduction

Active queue management (AQM) [7] has been a popular research area in recent years. The basic philosophy of AQM is to trigger packet dropping (or marking, if explicit congestion notification (ECN) [8] is enabled) before the buffer overflows, and when drop probability is proportional to the degree of congestion. In existing AQM schemes, link congestion is estimated through queue length, input rate, events of buffer overflow and emptiness, or a combination of these factors. Queue length (or average queue length) is widely used in Random Early Detection (RED) [4] and most of its variants [3, 9-10], in which packet drop probability is often linearly proportional to queue length. Stabilized RED (SRED) [3, 16] and BLUE [11] trigger to adjust the packet drop probability when the packet buffer is overflowing or empty. The traffic input rate is also used in some AQM schemes such as Adaptive Virtual Queue algorithm (AVQ) [12] to make them more adaptable to instantaneous traffic variance and to achieve the desired link utility. Some recent AQM schemes, such as Proportional Integral (PI) [13-14], Random Exponential Marking (REM) [2], and state feedback controller SFC [15], jointly use queue length and traffic input rate [7].

AQM [1] can be classified into two types: 1) rate-based, which controls the flow rate at the congested link (e.g., [2]), and 2) queue-based, which controls the queue at the congested link (e.g., [3], [4]). Random early detection (RED) gateways and many other algorithms have been proposed for AQM. The RED algorithm uses the averaged queue length for congestion control [4]. The loss ratio based RED (LRED) [5] measures the latest packet loss ratio, and uses it as a complement to queue length in order to dynamically adjust packet drop probability. The VRC scheme is based on rate control to maintain the packet input rate around the link capacity.

In this paper, we propose an LRC-RED scheme, which is based on the LRED and VRC algorithms. The LRC-RED scheme incorporates packet loss ratio and the total input rate (in addition to queue length and link capacity) for congestion estimation. Under LRC-RED, packet drop probability is updated under multiple time-scales. At the packet level, LRC-RED uses instantaneous queue mismatch and the total input rate mismatch to update packet drop probability upon the arrival of new packets. On larger time-scales, LRC-RED dynamically adjusts the packet drop probability using the measured packet loss ratio and the sending rate. Through ns simulations, we show the effectiveness of the proposed LRC-RED as compared with the LRED algorithm.

Stability in the performance of AQM scheme is essential due to the fact that, under stability state oscillations in queue size or deviations in queue size from the desired operating points or regions are reduced. Benefits of stabilizing queue size are utilization improvement and average queuing delay reduction by avoiding buffer overflows and oscillatory behaviors in the TCP sources. From an operational point of view, this is important especially, considering those buffer size limitations in routers. Furthermore, an unstable system often leads to strong synchronization among TCP flows. Bearing this in mind, in this paper we will consider the stabilization of queue size when setting the parameters.

To overcome the difficulty of parameter settings in AQM schemes, by using the feedback control theory of time-delayed systems and the TCP/RED dynamic model, this paper establishes an explicit condition under which the TCP/RED system is stable in terms of the instantaneous queue level. On the basis of this stability condition we develop a simple, scalable and systematic rule of tuning the parameters, in which these key parameters are decoupled from other tuning parameters as well as the network condition related parameters. Further, they are adapted within a dynamically changing range, which are determined by the stability condition. Henceforth, we are able to propose a new configuration of LRC-RED to enhance the performance of networks. Both theoretic analyses and simulation results will show the superiority of the new RED configuration over the LRC-RED on the aspects of self-tuning, robust and adaptive features.

In what follows, we describe the proposed scheme, LRC-RED in Section II. In Section III, we represent our main result on the stability of TCP/RED systems which is yielded from control theoretic analyses treating the systems of TCP dynamic model [10, 13] integrated with the LRC-RED dropping equation as time-delayed feedback systems. We then carry out simulations under a variety of network scenarios to confirm better performance of our algorithm than L-RED in Section IV. Finally, Section V provides the concluding remarks.

2. The LRC-RED Scheme

The LRC-RED scheme periodically measures the packet loss ratio; let $l(k)$ be the packet loss ratio during the latest M measurement periods, i.e., the ratio of the number of dropped packets to the number of total arrival packets during the latest M measurement periods. If packets are of different sizes, $l(k)$ can be calculated as the ratio of the total dropped bytes against the total arrival bytes, and can be denoted by

$$l(k) = \frac{\sum_{i=0}^{M-1} N_d(k-i)}{\sum_{i=0}^{M-1} N_a(k-i)}, \qquad (1)$$

where $N_d(k)$ is the number of packets dropped in the k-th period, and $N_a(k)$ is the number of packets arrived in the k-th period. Therefore, the measured packet loss ratio $\overline{l(k)}$ can be calculated at the end of each measurement period as follows:

$$\overline{l(k)} = \overline{l(k-1)} * mv + (1-mv) * l(k), \qquad (2)$$

where mv is the measured weight factor, which is set to a small value in order to track the current loss ratio.

After calculating the packet loss ratio, the task is to find some methods to calculate packet drop probability using instantaneous queue length and the total input rate as input variables, according to the design rules for small time scales, as listed above. These methods should provide an average packet drop probability that is as close as possible to the measured packet loss ratio. Therefore, to achieve the goals of stabilizing instantaneous queue length at the queue target and achieving high link utilization, we design the following drop probability p function based on the LRED [5] and VRC [6] schemes.

$$p(t) = \overline{l(k)} + \alpha\sqrt{\overline{l(k)}}(q(t)-q_t) + \beta(r(t)-C), \qquad (3)$$

Where α and β are the pre-configured control gains; *p*: Probability of packet drop; *p(t)*: Time-derivative of *p*; *q*: Current queue length (packets); q_t: the target of queue length (packets); *C*: Capacity of link (packets per second); *r*: the total input rate [packets/sec]. From equation (3), we find that when the system is stable, the instantaneous queue length can be stabilized at the queue target and the system has higher link utilization.

3. Stability Analysis and Control gain selection

3.1. Model of Combined TCP/AQM System

We use the TCP model of [3] as described by the following equations:

$$\dot{W}(t) = \frac{1}{R(t)} - \frac{W(t)W(t-R(t))}{aR(t-R(t))}p(t-R), \quad (4)$$

$$\dot{q}(t) = N(t)\frac{W(t)}{R} - C. \quad (5)$$

where the variables are defined as follows: W: Expected TCP window size (packets); $\dot{W}(t)$: Time-derivative of W; N: Load factor (number of TCP connections); R: Round-trip time, i.e., the sum of q/C (the processing time of buffer queue) and Tp (propagation time of packet in the link). Assume the round trip delay $R(t)$[sec] and the number of TCP connections N (t) are both constant，i.e., $R(t) = R$, $N(t) = N$. And substitute the window size $W(t)$ for the total input rate $r(t)$ [packets/sec]，i.e., $r(t) = NW(t) / R$. Then the equation (1) and (2) can be described as follows:

$$\dot{r}(t) = f(r,p) = \frac{N}{R^2} - \frac{1}{\gamma \cdot N} r(t)r(t-R)p(t-R), \quad (6)$$

$$\dot{q}(t) = g(r,p) = r(t) - C. \quad (7)$$

The input rate at the equilibrium point can be obtained by the equation $\dot{r}(t) = 0$. The γ value of 2/3 would be appropriate to give the steady-state throughput of TCP of $\sqrt{(3/2)/p^*}/R$ where p^* is the steady-state marking probability. Henceforth, we will use γ = 2/3 in all calculations. The equilibrium point of the non-linear TCP/AQM model (3)、(6) and (7) is given by：

$$r^* = C,\ p^* = \frac{aN^2}{R^2C^2}, q^* = q_t.$$

Assume the measured packet loss ratio can be used to approximate the stable packet drop probability, i.e., $\overline{l(k)} \approx p^*$. Hence, we can rewrite equation (3) as:

$$p(t) = p^* + \alpha\sqrt{p^*}(q(t) - q_t) + \beta(r(t) - C), \quad (8)$$

let $q(t) = q^* + \delta q(t)$, $p(t) = p^* + \delta p(t)$, and $r(t) \approx r(t-R)$ [4], then the linearized model of a non-linear TCP/AQM model around the equilibrium point (r^*, q^*, p^*) can now be written as:

$$\delta \dot{r}(t) = \frac{\partial f}{\partial r}\delta r + \frac{\partial f}{\partial p}\delta p = -[K_{11}\delta r + K_{12}\delta p(t-R)], \quad (9)$$

$$\delta \dot{q}(t) = \frac{\partial g}{\partial r}\delta r + \frac{\partial g}{\partial p}\delta p = K_{21}\delta r, \quad (10)$$

$$\delta p(t) = \alpha\sqrt{p^*}\delta q + \beta\delta r, \quad (11)$$

where $K_{11} = \frac{2N}{R^2C}$, $K_{12} = \frac{3RC^2}{2N^2}$ and $K_{21} = \frac{N}{R}$.

Applying a Laplace transform to equations (9)、(10) and (11)，we have

$$sr(s) = -K_{11}r(s) - K_{12}p(s)e^{-Rs}, \quad (12)$$

$$sq(s) = K_{21}r(s), \quad (13)$$

$$p(s) = \alpha\sqrt{p^*}q(s) + \beta r(s), \quad (14)$$

Then we can get the Characteristic Polynomial (CP) of the system based on the above equations (12)、(13) and (14) as follows：

$$\Delta(s) = \det(s^2 + K_{11}s + K_{12}(\alpha\sqrt{p^*}K_{21} + \beta s)e^{-Rs}) = 0 \quad (15)$$

In the following we will prove the system stability based on the conclusions [4-5] of control theory.

3.2. Stability analysis

Theorem 1: The TCP/IP system described by (4) and (5) is asymptotically stable for all $R \geq 0$, if and only if

$$\beta > -\frac{K_{11}}{K_{12}},\ 0 < \alpha < \frac{(K_{11} + K_{12}\beta)(1 + K_{11}R)}{K_{12}K_{21}R\sqrt{p^*}}. \quad (16)$$

Prove：let $z = e^{-Rs}$, where z is a complex，then the equation (14) can be rewritten as：

$$\Delta(s) = a_0 s^2 + a_1 s + a_2 = 0 \quad (17)$$

where $a_1 = K_{11} + \beta z,\ a_2 = K_{12}\alpha\sqrt{p^*}K_{21}z.$

Next, we will construct a Hermite Matrix $H = \begin{bmatrix} (0,1) & (0,2) \\ (0,2) & (1,2) \end{bmatrix}$, where

$$(0,1) = i^{0+1+1}((-1)a_0\bar{a}_1 + (-1)\bar{a}_0 a_1) = a_0\bar{a}_1 + \bar{a}_0 a_1 = 2K_{11} + \beta(z + \bar{z}), \quad (18)$$

$$(0,2) = i^{0+2+1}((-1)^2 a_0 \bar{a}_2 + (-1)^1 \bar{a}_0 a_2)$$
$$= -i(a_0\bar{a}_2 - \bar{a}_0 a_2) = -iK_{12}\alpha\sqrt{p^*}K_{21}(\bar{z} - z), \quad (19)$$
$$(1,2) = i^{1+2+1}((-1)^2 a_1\bar{a}_2 + (-1)^2 \bar{a}_1 a_2) = a_1\bar{a}_2 + \bar{a}_1 a_2$$
$$= K_{11}K_{12}\alpha\sqrt{p^*}K_{21}(z+\bar{z}) + \beta K_{12}\alpha\sqrt{p^*}K_{21}|z|^2 \quad (20)$$

Let $z = e^{iw}$, then

$$H(e^{iw}) = \begin{bmatrix} 2(K_{11}+\beta\cos w) & -2K_{12}\alpha\sqrt{p^*}K_{21}\sin w \\ -2K_{12}\alpha\sqrt{p^*}K_{21}\sin w & K_{12}\alpha\sqrt{p^*}K_{21}(2K_{11}\cos w+\beta) \end{bmatrix}. \quad (21)$$

Condition 1： $H(1) = H(e^{i0})$ is positive definite, in other words, the sequential principal minors of $H(1)$ are all positive.

Then we have $\begin{cases} \alpha > 0 \\ \beta > -K_{11} \end{cases}$. (22)

Condition 2： $\det H(e^{i\omega}) > 0$, for all $\omega \in [0, 2\pi]$.

$$\det(H(e^{iw})) = 2(K_{11} + \beta\cos w)\, K_{12}\alpha\sqrt{p^*}K_{21}$$
$$\cdot (2K_{11}\cos w + \beta) - (2K_{12}\alpha\sqrt{p^*}K_{21}\sin w)^2 > 0$$

Then we have the following results based on the above inequality:

when $\alpha = \dfrac{-K_{11}\beta}{K_{12}K_{21}\sqrt{p^*}}$,

$$\beta^2 - K_{11}(2\alpha+1)\beta + 2K_{11}{}^2 > 0;$$

when $\alpha \neq \dfrac{-K_{11}\beta}{K_{12}K_{21}\sqrt{p^*}}$,

$$\begin{cases} \alpha\beta > 0 \\ K_{11} < \beta < 2K_{11} \end{cases}. \quad (23)$$

Therefore, from (22) and (23), we obtain

$$\beta > -\frac{K_{11}}{K_{12}}, \; 0 < \alpha < \frac{(K_{11} + K_{12}\beta)(1 + K_{11}R)}{K_{12}K_{21}R\sqrt{p^*}}.$$

4. Simulation Results

In this section, we investigate the performance of the proposed LRC-RED scheme, through ns-2 [7] simulations. We also compare its performance with existing AQM schemes, in particular, LRED [5] and VRC [6]. For LRC-RED, the parameters for loss ratio measurement (Eqs. (1) and (2)) are as same as those of the LRED scheme, i.e., *mw = 0.1, mp = 1.0s, M = 4.*

The network topology for simulation is the commonly used dumb-bell topology (see Fig. 1): We chose all the parameter values to be as those used in the first experiment of [6], namely, there is a single congestion link from router 1 to router 2, and the capacity of each link is 10Mbps. The link delay between Client *c(i)* and router 1 is labeled as a 5-tuple (*d1, d2, d3, d4, d5*) with a unit of millisecond (ms). All flows are uniformly distributed among pairs of Client *c(i)* and Server *s(i)*. The packet size is 500 bytes, and the buffer size of each router is 200 packets. The round trip time is 210 ms; the number of FTP flows is 180. The queue target is 100 packets. Based on Theorem 1 and the above network setting, we set the control gains α = 0.01 and β = 0.1 to satisfy these parameters in the stability area. We ran each simulation for 200 seconds, which is long enough to observe transient as well as steady-state behaviors of the AQM schemes.

In this simulation, we focused on the following key performance metrics: instantaneous queue length, link utilization and average absolute queue deviation. Average queue deviation is defined as the absolute deviation between instantaneous queue length and its mean value.

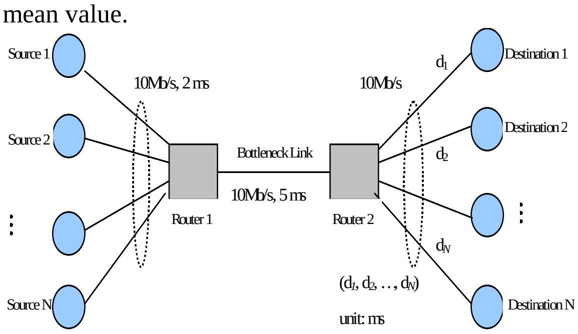

Fig. 1. Network topology

We first compare the stability of queue length for LRC-RED and LRED, as in [5]. In this case, *N=80* and ms *d1= d2= d3= d4= d5 = 250* ms.

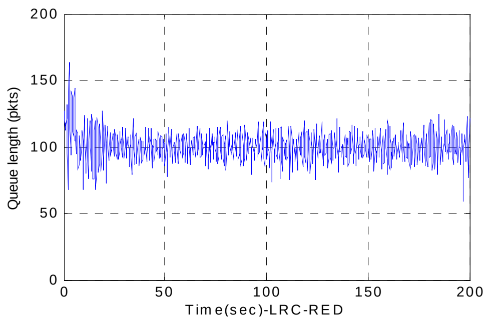

Fig. 2. Queue length based on LRC_RED in light congestion

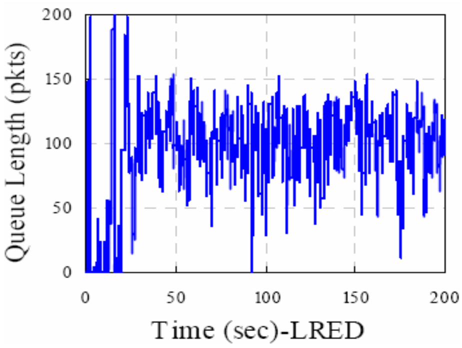

Fig. 3. Queue length based on LRED in light congestion

Fig. 2 and Fig. 3 present the instantaneous queue length of each AQM scheme for the two cases. It can be seen that, with light congestion, the queue length of LRED oscillates nearly out of control, while LRC-RED still stably regulates the queue. In this case, with large RTT, LRC-RED has a slightly increased response time, because TCP needs more rounds to reach a stable value W_0 of its congestion window (*cwnd*) at this time. In summary, LRC-RED shows better stability and quick response under either light congestion or heavy congestion. And the LRC-RED scheme has better robustness than the LRED algorithm.

5. Conclusions

In this paper, we propose a new AQM scheme, LRC-RED, which incorporates packet loss ratio and total input rate (in addition to queue length and link capacity) for congestion estimation. We analyzed stability, response time and link utilization of LRC-RED. We also conducted extensive simulations to evaluate its performance, and compared it with the LRED scheme. Our results showed that LRC-RED has a shorter response time than LRED. More importantly, LRC-RED achieves better stability and robustness than LRED in dynamic environments. Finally, LRC-RED can effectively control the queue length to an expected value. In summary, LRC-RED is an effective scheme for ensuring system stability and robustness.

10. References

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