LQ-Servo Congestion Control for TCP/AQM System in Wireless Network Environment

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Abstract

This paper presents LQ-Servo controller for congestion control in TCP/AQM wireless networks environment using previously developed controller. A wireless networks link has a capacity which is time-varying. For this, it is modeled by three-state mode for considering the dynamics of wireless links in this paper. And the proposed controller structure is made by augmenting a new state variable to the feed-forward loop.

Keywords: *Congestion Control, LQ-Servo, TCP/AMQ, Wireless Networks*

1. Introduction

Computer networks have increased congestion collapse problems according to growth of wired or wireless network. This leads to network congestion and comes to more important issues for high packet loss rate due to buffer overflow. Also, it is harder to detect if there are wireless links in the network environment. Jacobson and Karels [1] proposed the end-to-end congestion control algorithm which forms the basis for the TCP (Transmission Control Protocol) congestion control. Floyd and Jacobson [2] presented the RED (Random Early Detection). Its mechanism is that packets are randomly dropped before the buffer of queue overflows.

In general AQM (Active Queue Management) schemes enhance the performance of TCP and the feedback control theory is able to help to solve congestion control problem. Misra, *et al.*, [3] developed a methodology to model and obtain expected transient behavior of networks with AQM supporting TCP flows. Hollot, *et al.*, [4] approximated its linearized model using small-signal linearization in order to convert to control problem based on feedback control theory, and designed the PI controller [5].

More recently, Yang and Suh [6] proposed the robust PID (Proportional-Integral-Derivative) controller based on LQ (Linear Quadratic) approach for AQM system. And Lee and Yang [7] proposed the LQ-Servo controller structure, and then Yang, *et al.*, [8] developed the tuning method of controller parameter based on Loop-Shaping [9]. But, they did not apply the wireless networks environment.

For applying TCP/AQM in wireless networks environment, it should be considering the dynamics of wireless links, then the TCP/AQM wireless networks system is modeled using three states in this paper. And we propose a robust congestion control for an extension version of previous works [7] and [8] in order to apply wireless networks environments.

2. Model of TCP/AQM

This section introduces a mathematical model of TCP/AQM system to convert a control theoretical approach based on [3] and [4].

2.1. Nonlinear Dynamic Model

It can be modeled the TCP/AQM network by a simple topology in wireless networks link as shown in Figure 1. TCP sender sources will be to send data in the direction of destinations through a route, which indicates the bottleneck node in the network.

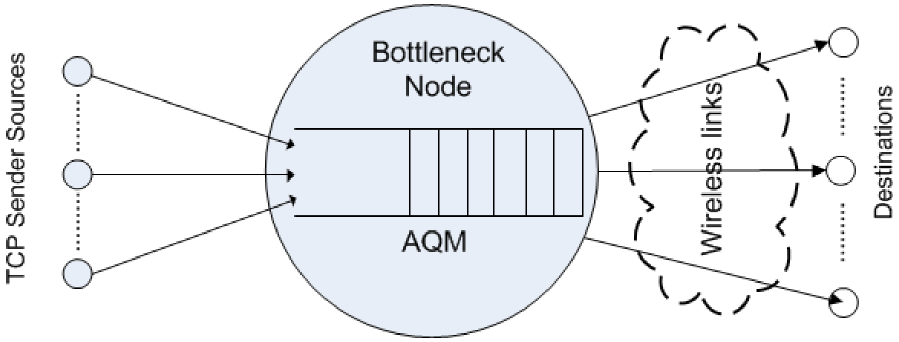


Figure 1. TCP/AQM simple network topology

A nonlinear dynamic model as shown in Figure 2 for TCP/AQM systems is presented using fluid-flow and stochastic differential equation in [3] in wired networks, which is as following:

$$\begin{aligned} \dot{W}(t) &= \frac{1}{R(t)} - \frac{W(t)W(t-R(t))}{2R(t-R(t))} p(t-R(t)), \\ \dot{q}(t) &= \frac{W(t)}{R(t)} N(t) - C \end{aligned} \tag{1}$$

where $\dot{W}(t)$ denotes the time-derivative of $W(t)$, $\dot{q}(t)$ denotes the time-derivative of $q(t)$, $W \doteq$ Expected TCP window size (packets), $q \doteq$ Expected queue length (packets), $R_0 \doteq$ Round-trip time (seconds) $= q/C + T_p$, $C \doteq$ Link capacity (packets/second), $N \doteq$ Load factor (number of TCP sessions), $p \doteq$ Probability of packet mark/drop, $T_p \doteq$ Propagation delay (sec), and $t =$ Time. The expected queue length q and the expected TCP window size W are positive value and bounded quantities. And also, the probability of packet mark (drop) p takes value only in $0 \le p \le 1$.

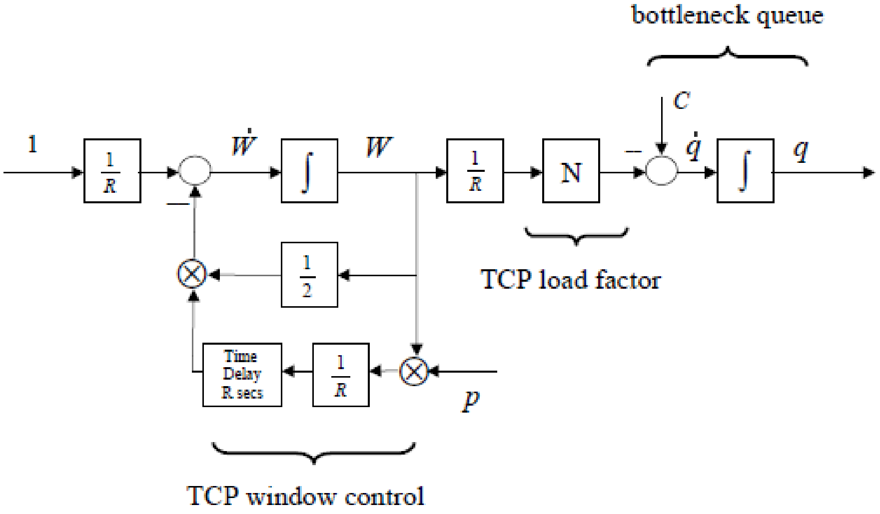


Figure 2. Block-diagram of TCP flow model (refer to [4])

2.2. Linearized Model

In order to linearize for wired networks, it is assumed that the number of TCP sessions and the link capacity are constant, and then a linearized constant model can be approximated by small-signal linearization about an operating point (W_0, q_0, p_0) defined by $\dot{W} = 0$ and $\dot{q} = 0$, see [4] for linearization details. The linearized model can be presented in (1)

$$\begin{aligned} \delta\dot{W}(t) &= -\frac{2N}{R_0^2 C}\delta W(t) - \frac{R_0 C^2}{2N^2}\delta p(t - R_0), \\ \delta\dot{q}(t) &= \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t) \end{aligned} \tag{2}$$

where $\delta W(t) \doteq W - W_0$, $\delta q(t) \doteq q - q_0$ and $\delta p(t) \doteq p - p_0$

The transfer function of TCP/AQM model indicates as following:

$$P(s) = P_{tcp}(s) P_{queue}(s) e^{-sR_0} = \frac{\frac{C^2}{2N}}{(s + \frac{2N}{R_0^2 C})(s + \frac{1}{R_0})} e^{-sR_0} \tag{3}$$

where $P_{tcp}(s)$ denotes the transfer function from loss probability $\delta p(t)$ to window size $\delta W(t)$, $P_{queue}(s)$ denotes the transfer function from $\delta W(t)$ to queue length $\delta q(t)$.

The block diagram of linearized TCP/AQM model is illustrated in Figure 3, where $C(s)$ denotes the transfer function of controller.

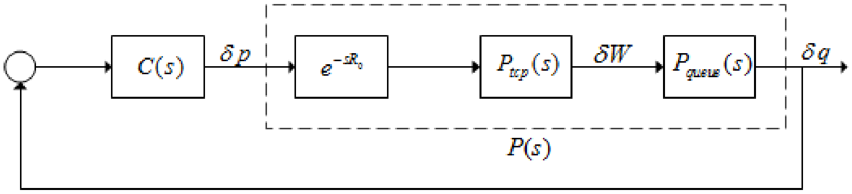


Figure 3. Block-diagram of the linearized TCP/AQM model

2.3. State-Space Model

Let the state variable $x_p(t)$ be defined as:

$$x_p(t) = \begin{bmatrix} x_r(t) \\ y_p(t) \end{bmatrix} = \begin{bmatrix} \delta W(t) \\ \delta q(t) \end{bmatrix} \tag{4}$$

and (2) can be represented with state-space model:

$$\begin{aligned} \dot{x}_p(t) &= A_p x_p(t) + B_p u(t - R_0) \\ y_p(t) &= C_p x_p(t) \end{aligned} \tag{5}$$

where $y_p(t) = \delta q(t)$ is an output variable, $u(t - R_0) = \delta p(t - R_0)$ is a input-time-delayed control variable. And the system matrix, input matrix and output matrix of (5) can be expressed as following:

$$A_p = \begin{bmatrix} -\dfrac{2N}{R_0^2 C} & 0 \\ \dfrac{N}{R_0} & -\dfrac{1}{R_0} \end{bmatrix}, B_p = \begin{bmatrix} -\dfrac{R_0 C^2}{2N^2} \\ 0 \end{bmatrix}, C_p = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{6}$$

3. Design of LQ-Servo Controller

This section presents LQ-Servo controller for TCP/AQM based on Linear Quadratic approach.

3.1. Extending State-Space Model

For extending the state variable with an augmented state variable $z_p(t)$, the state variable $x(t)$ can be extended as:

$$x(t) = \begin{bmatrix} x_p(t) \\ z_p(t) \end{bmatrix} = \begin{bmatrix} x_r(t) \\ y_p(t) \\ z_p(t) \end{bmatrix} = \begin{bmatrix} \delta W(t) \\ \delta q(t) \\ \int_0^t q(\tau)\, d\tau \end{bmatrix} \tag{7}$$

Then, the state-space model (5) can be represented as following:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t - R_0) \\ y(t) &= Cx(t)\end{aligned} \tag{8}$$

where the system matrix, input matrix and output matrix of (8) can be expressed as:

$$A = \begin{bmatrix} A_p & 0 \\ C_p & 0 \end{bmatrix}, B = \begin{bmatrix} B_p \\ 0 \end{bmatrix}, C = \begin{bmatrix} C_p & 0 \end{bmatrix} \tag{9}$$

3.2. LQ-Servo Controller

An optimal servo problem via Linear Quadratic approach, that is called LQ-Servo, is to find the optimal control law $u(t)$ by minimizing a cost function as:

$$J = \int_0^\infty \{x^T(t) \cdot Q \cdot x(t) + u(t) \cdot \rho \cdot u(t)\} dt \tag{10}$$

where a weighting matrix Q is symmetric and positive semi-definite, and a weighting factor ρ is positive value.

Then, we use the general control law

$$u(t) = -G\, x(t) \tag{11}$$

where $G = -\rho^{-1} B^T K$ and $K = K^T$ is a solution matrix of the algebraic Riccatti's equation:

$$KA + A^T K + Q - \frac{1}{\rho} KB\, B^T K = 0 \tag{12}$$

Suppose the gain matrix G is decomposed into $G = \begin{bmatrix} g_r & g_y & g_z \end{bmatrix}$, the optimal control input of (11) can be expressed by the augmented state-variable $x(t)$ of (7) as:

$$u(t) = -g_r x_r(t) - g_y y_p(t) - g_z z_p(t) \tag{13}$$

Therefore, the LQ-Servo controller structure of TCP/AQM is shown in Figure 4 to ensure that zero steady state error is robustly achieved in response to varying reference commands.

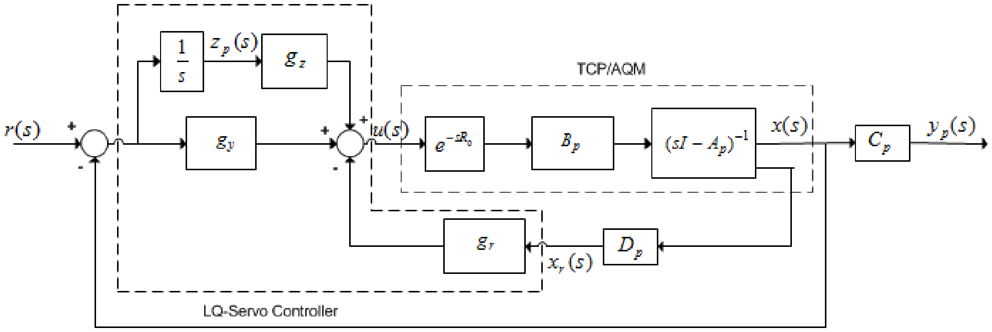


Figure 4. LQ-Servo controller structure for TCP/AQM

3.3. TCP/AQM Control for Wireless Networks

In wireless networks environment, it should be noted that system parameter are sensitive to varying channel conditions and data rates. This means that an adapting congestion controller is an important issue in the given varying wireless link such as node, capacity and round-trip time. For this, the TCP/AQM wireless networks system is modeled using three states as shown in Figure 3. State transitions would occur due to wireless channel variations, and then the wireless networks environment can be defined by these transitions in this paper.

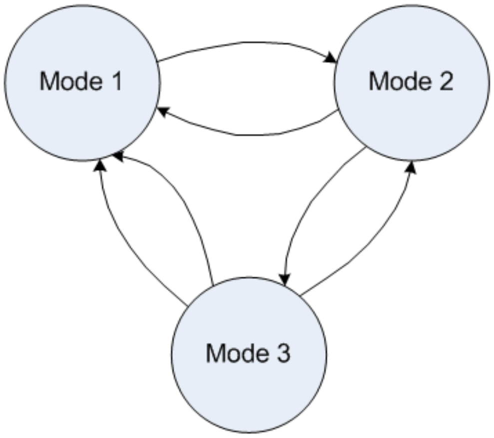


Figure 5. State transition diagram for wireless networks environment

So, the controller is required to be robust with respect to the time-varying network parameter like queue capacity and number of TCP sender source. It can be represented the TCP/AQM controller model for a wireless networks environment as shown in Figure 6.

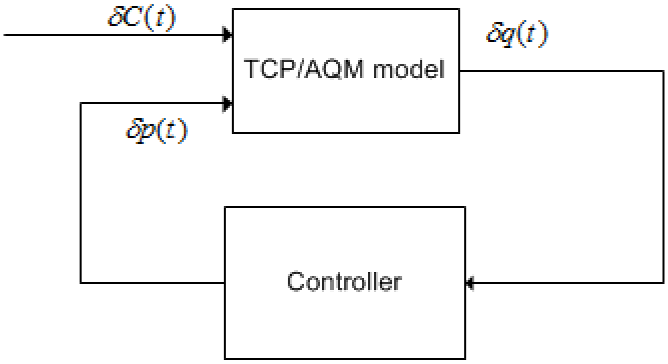


Figure 6. Block-diagram of TCP/AQM controller for a wireless networks

The inputs to a TCP/AQM model are the probability of packet drop $\delta p(t)$ and the capacity variations $\delta C(t)$, and the output is the queue length $\delta q(t)$.

Therefore, we can obtain a state-space model of linearized TCP/AQM system for a wireless networks environment according to the time-varying capacity $\delta C(t)$ using the above nonlinear model of TCP dynamic as following:

$$\begin{bmatrix} \delta\dot{W}(t) \\ \delta\dot{q}(t) \end{bmatrix} = \begin{bmatrix} -\dfrac{2N}{R_0^2 C} & 0 \\ \dfrac{N}{R_0} & -\dfrac{1}{R_0} \end{bmatrix} \begin{bmatrix} \delta W(t) \\ \delta q(t) \end{bmatrix} + \begin{bmatrix} -\dfrac{R_0 C^2}{2N^2} & 0 \\ 0 & \dfrac{q}{R_0} \end{bmatrix} \begin{bmatrix} u(t-R_0) \\ \delta C(t) \end{bmatrix} \tag{14}$$

$$y_p(t) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} \delta W(t) \\ \delta q(t) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u(t-R_0) \\ \delta C(t) \end{bmatrix}$$

4. Simulation

For simulations in this paper, the basic network topology is shown in Figure 7 and the system parameters have 3-modes taken in Table 1.

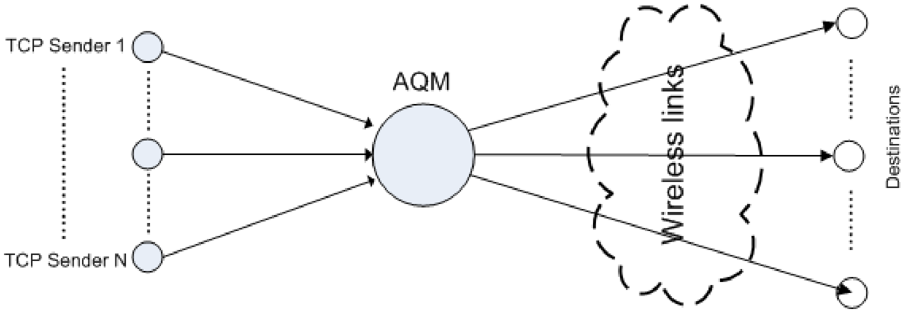
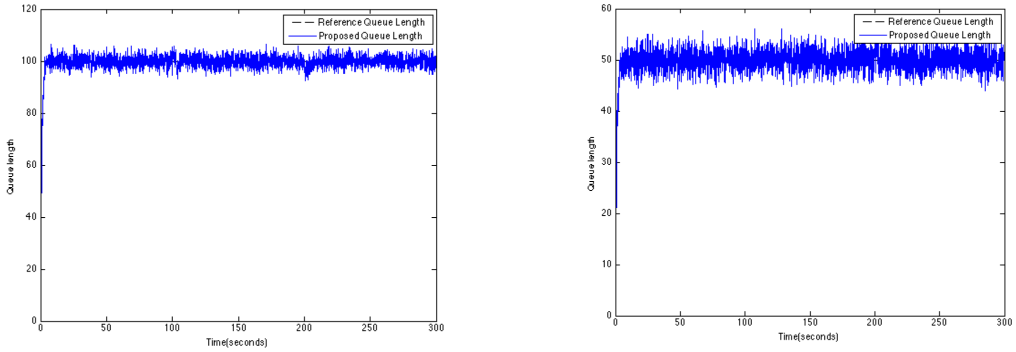


Figure 7. TCP/AQM wireless networks topology

Table 1. System parameters of 3-mode for Wireless Networks

Mode 1	Mode 2	Mode 3
$N = 100$ $C = 1875\, packets / \sec$ $R_0 = 0.2$	$N = 50$ $C = 950\, packets / \sec$ $R_0 = 0.1$	$N = 20$ $C = 1500\, packets / \sec$ $R_0 = 0.5$

At every 100 seconds, the mode is changed ((a) reference queue length: 100 (b) reference queue length: 50) from Mode 1 to Mode 3. The simulation results are shown in Figure 8. The proposed LQ-Servo controller is robust against the 3-modes, and the queue length does not fluctuated.



(a) (b)

Figure 8. Simulation results

5. Conclusion

Although the congestion control algorithm for TCP/AQM have been extensively proposed for a wired networks, the design of control for a wireless networks has not been adequately addressed. This paper present LQ-Servo controller for congestion control in TCP/AQM wireless networks environment based on preciously developed controller. The controller structure is made by augmenting a new state variable. And a wireless networks environment is considered by three-state mode with respect to the dynamics of wireless links in this paper.

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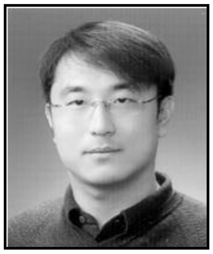

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