

Design of robust AQM controllers for improved TCP Westwood congestion control

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Abstract

This paper is concerned with the application of a novel robust AQM controller recently presented in the literature to TCP Westwood congestion control. The aim is twofold. Firstly we assess the performance of the scheme when applied to networks where the traffic is generated by sources controlled by Westwood TCP. Secondly, we validate the controller through numerical simulations showing that it guarantees better performance in the presence of unwanted variations of the load, the round trip time and the link capacity when compared to other existing AQM control schemes.

I. INTRODUCTION

Traditional TCP implements an end-to-end congestion control mechanism based on the fundamental assumption that routers implements a drop tail policy so that packet losses are due to congestion [15]. When a packet loss is detected by timeout or 3 duplicate acknowledgements the TCP congestion controller reacts by multiplicatively shrinking the congestion window, i. e. the sending rate. On the other hand, each time a packet is successfully acknowledged the TCP linearly increments the congestion window. Interesting mathematical models of the closed loop behaviour of the TCP have been proposed in literature [16]-[19]. These models provide differential stochastic equations that relate the packet drop probability with the congestion window dynamics. The basic idea of Active Queue Management is to actively throttle the packet drop rate in order to affect the TCP input rate and provide a nice behaviour of TCP flows, such as low queuing delays, or traffic differentiation, or control of misbehaving flows and so on. Since the first time that AQM was proposed in [20] as a simple Random Early Discard policy (RED), it was clear how difficult was to tune the AQM controller, which, as a matter of fact, delayed the employment in real routers. As a consequence, a consistent amount of literature has been devoted to the issue of designing controllers for actively throttling the packet drop rate [19],[21]. Beside the usual AQM controls, i.e. RED, PI, perform poorly in the presence of network parameter variations such as round-trip time, load variations and link capacity which are bound to occur in more realistic networks. Indeed in more realistic networks, the round-trip time can also vary with respect to its nominal value because of congestion phenomena and other effects such as the presence of responsive sources variations at different points in the network (causing the variation of equivalent round trip time propagation delay), rerouting, additional unresponsive source traffic. Also the assumption of fixed long-lived TCP workload, often taken in the derivation of these models, is also violated in realistic network scenarios. Moreover variations in the link capacity advertised from long-lived TCP flows can also occur because of unresponsive traffic generated by UDP and short-lived TCP flows. Thus, the ultimate aim of AQM control is to design a strategy taking explicitly into account the presence of round trip time delays in the network model and to make the system robust against network parameter uncertainties while guaranteeing acceptable performances in terms of margin stability, reduced number of packet losses, a more efficient queue utilization and better regulation, and shorter queuing delays. Recent robust control technics are applied to AQM with comfortable results in Simulink and NS-2 simulations [9], [10]. In this paper we consider TCP flows controlled by Westwood+ TCP, which is a new end-to-end sender based modification of standard TCP that employs the stream of returning acknowledgment packets to estimate the available bandwidth and set the congestion window after congestion [2],[3]. After developing a mathematical model of Westwood+ TCP, we propose a robust AQM control approach on this model able to cope with unwanted variations of characteristic parameters such as the average round-trip time, load and link capacity, just proposed in [9], [10] for Hollot's model [22]. In particular: (1) an appropriate robust control method for time-delay systems is proposed to cope with round-trip time, load variations and link capacity and hence used to design a suitable AQM control scheme; (2) A robust observer based on the mathematical model of the Westwood+ TCP source behaviour is used in the control loop to avoid direct measurement of the congestion window, as this would be impractical in applications. Finally, the resulting control law is validated and tested through numerical simulations.

II. TCP-WESTWOOD: AN OVERVIEW

The basic idea of TCP Westwood is to exploit the stream of returning ACK packets in order to obtain an estimate of the connection available bandwidth (*BWE*). The bandwidth estimate is used when a congestion episode is detected to

properly set the $cwnd$ and $ssthresh$. In the absence of congestion, the dynamics of these variables is conform to RFC2581 [1]. A pseudo-code of the Westwood TCP algorithm can be given as follows:

- When 3 DUPACKs are received:
 - $ssthresh = (BWE * RTT_{min}) / MSS$;
 - if ($ssthresh < 2$) $ssthresh = 2$;
 - $cwnd = ssthresh$;
- When coarse timeout expires:
 - $ssthresh = (BWE * RTT_{min}) / MSS$;
 - if ($ssthresh < 2$) $ssthresh = 2$;
 - $cwnd = 1$;
- When ACKs are successfully received:
 - $cwnd$ increases as stated in RFC2581.

It is worth noting that the adaptive decrease mechanism employed by TCP Westwood improves the stability of the standard TCP multiplicative decrease. In fact, the adaptive window shrinking provides a congestion window that is decreased enough in the presence of heavy congestion and not too much in the presence of light congestion or losses not due to a real congestion episode, such as in the case of unreliable radio links. Moreover the setting $cwnd = BWE * RTT_{min}$ injects a transmission rate equal to $BWE * RTT_{min} / RTT$, which is less than bandwidth used at the time of congestion. As a consequence, a Westwood TCP flow clears out its path backlog after the setting thus leaving room in the routers' buffers for coexisting flows. This obviously improves network stability, statistical multiplexing and fairness.

TCP Westwood congestion control is heavily based on bandwidth estimation algorithm. Bandwidth estimation algorithm proposed in [2] overestimates the available bandwidth in the presence of ACK compression [3]. In order to avoid this undesirable behavior, Westwood+ TCP proposes a new bandwidth estimation algorithm that works properly also in the presence of ACK compression [3]. The new bandwidth estimation algorithm proposed along with Westwood+ TCP relies on bandwidth samples which are collected every RTT instead that every time an ACK is received by the sender. Basically, the Westwood+ TCP sender counts the amount of data D_k , which is acknowledged during the last $RTT = T_k$ and then computes a bandwidth samples as $B_k = D_k / T_k$. Details concerning the ACK counting can be found in [2]. Briefly, a duplicate ACK counts for one delivered segments, a delayed ACK for two segments, whereas a cumulative ACK counts for 1 segment or for the number of segments exceeding those already accounted for by previous duplicate acknowledgments. Since congestion depends on low frequency components of available bandwidth [4], B_k samples are filtered using a discrete time low-pass filter, details of the filtering algorithm can be found in [3].

A. A Fluid flow Model for Westwood TCP

This sub-section derives a fluid flow model of Westwood TCP by following the approach proposed in [5], [6]. We consider a packet switching network made of a single bottleneck with capacity C , shared by N Westwood TCP connections, all having the same round trip propagation delay T_p . In particular, under the assumption of neglecting the TCP timeout and the effect of the low-pass filter used to obtain the bandwidth estimation, the following set of nonlinear coupled ODEs is obtained:

$$\dot{W} = \frac{1}{\frac{q(t)}{C} + T_p} - \frac{W(t)W(t-R_0)}{\frac{q(t-R_0)}{C} + T_p} p(t-R_0) + T_p \left(\frac{W(t-R_0)}{\frac{q(t-R_0)}{C} + T_p} \right)^2 p(t-R_0) \quad (1)$$

$$\dot{q} = \begin{cases} -C + \frac{N}{\frac{q(t)}{C} + T_p} W(t) & \text{if } q > 0 \\ \max \left\{ 0, \frac{N}{\frac{q(t)}{C} + T_p} W(t) - C \right\} & \text{if } q = 0 \end{cases} \quad (2)$$

where $W(t)$ is the expected window size, $q(t)$ is the bottleneck queue size, R_0 is the round trip time at the equilibrium point and $p(t)$ is the packet loss probability, which is set by the AQM algorithm.

By assuming $p(t) = p_0$, $q(t) = q_0$ and $W(t) = W_0$, we can linearize the dynamic models (1) and (2) around the equilibrium point (q_0, W_0, p_0) . The following set of delay differential equations is obtained:

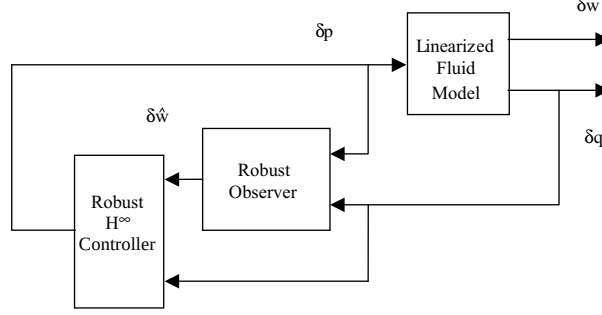


Fig. 1. Block Diagram of the proposed Robust H^∞ AQM control scheme.

$$\begin{aligned}
 \dot{\delta W} &= -\frac{N}{CR_0T_{q0}}[\delta W(t) + \delta W(t-R_0)(1-2\frac{T_p}{R_0})] + \\
 &\quad -\frac{1}{R_0^2C}[\delta q(t) - \delta q(t-R_0)(\frac{R_0-2T_p}{T_{q0}})] + \\
 &\quad -\frac{C^2R_0}{N^2}(1-\frac{T_p}{R_0})\delta p(t-R_0) \\
 \dot{\delta q} &= \frac{N}{R_0}\delta W - \frac{1}{R_0}\delta q(t)
 \end{aligned} \tag{3}$$

where $T_{q0} = R_0 - T_p$

By letting $x(t) = [\delta W, \delta q]^T$ and $u = \delta p$, the model (3) can be equivalently expressed as follows:

$$\dot{x} = Ax + A_d x(t-R_0) + B_d u(t-R_0) \tag{4}$$

where

$$\begin{aligned}
 A &= \begin{bmatrix} -\frac{N}{CR_0T_{q0}} & -\frac{1}{R_0^2C} \\ \frac{N}{R_0} & -\frac{1}{R_0} \end{bmatrix}, \\
 A_d &= \begin{bmatrix} -\frac{N}{CR_0T_{q0}}(1-2\frac{T_p}{R_0}) & \frac{1}{R_0^2C}(\frac{R_0-2T_p}{T_{q0}}) \\ 0 & 0 \end{bmatrix} \text{ and} \\
 B_d &= \begin{bmatrix} -\frac{C^2R_0}{N^2}(1-\frac{T_p}{R_0}) \\ 0 \end{bmatrix}.
 \end{aligned}$$

III. ROBUST H^∞ AQM CONTROL (RHC)

Now, we shall seek to use the model presented above to synthesize a robust AQM controller for networks with TCP Westwood traffic, which is robust to unwanted variations of parameter uncertainties as round trip time, load and link capacity. In so doing we will proceed in two stages. Firstly, an appropriate robust controller for time-delay systems will be synthesized for the linearized TCP fluid model (4) to cope with round-trip time, load and link capacity variations. Secondly, a robust observer will be designed to estimate the transmission window online, avoiding the requirement for full state availability. Such an observer will then be used to synthesize a robust AQM scheme which will be validated both numerically and experimentally on a realistic network scenario.

The resulting control scheme is shown in Fig. 1. In order to synthesize the controller and the observer in Fig. 1, we adapt to AQM control the theoretical design approaches presented in [13] and [11]. (A more detailed theoretical analysis of the scheme discussed here can be found in [9].)

The linearized TCP fluid model (3) can be rewritten as the uncertain time-delay system:

$$\begin{aligned}
 \dot{x}(t) &= (A + \Delta A(t))x(t) + (A_d + \Delta A_d(t))x(t-\tau) \\
 &\quad + (B_d + \Delta B_d(t))u(t-\tau), \\
 y &= Cx(t).
 \end{aligned} \tag{5}$$

with $x = (\delta W, \delta q)^T$, $u = \delta p$, $\tau = R_0$,

$$A = \begin{bmatrix} -\frac{N}{CR_0T_{q0}} & -\frac{1}{R_0^2C} \\ \frac{N}{R_0} & -\frac{1}{R_0} \end{bmatrix}, A_d = \begin{bmatrix} -\frac{N}{CR_0T_{q0}}(1-2\frac{T_p}{R_0}) & \frac{1}{R_0^2C}(\frac{R_0-2T_p}{T_{q0}}) \\ 0 & 0 \end{bmatrix} \text{ and } B_d = \begin{bmatrix} -\frac{C^2R_0}{N^2}(1-\frac{T_p}{R_0}) \\ 0 \end{bmatrix},$$

initial conditions $x(0) = \Psi(t)$, $t \in [-\tau, 0]$, and $u(t) = \Phi(t)$ for $t \in [-\tau, 0]$. $\Delta A(t)$, $\Delta A_d(t)$ and $\Delta B_d(t)$ represent time varying model uncertainties with appropriate form and dimensions depending on network parameters uncertainties.

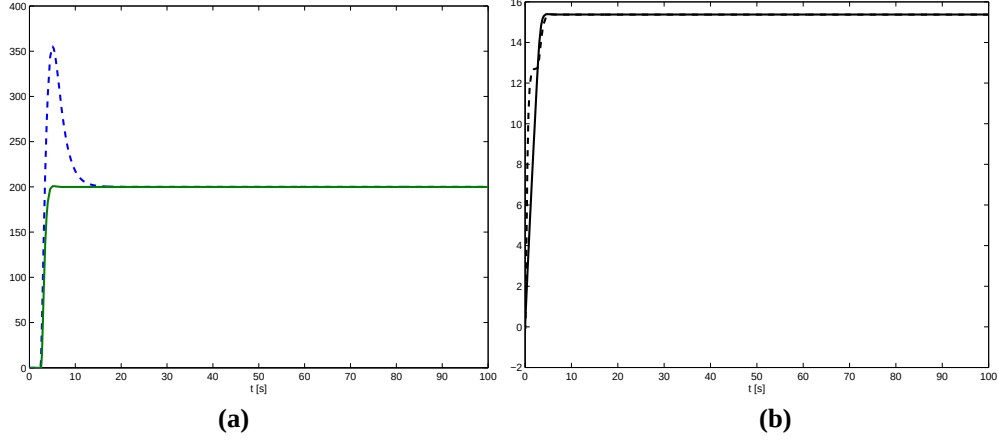


Fig. 2. Case 1: **(a)** Time evolution of the queue length for the PI-AQM (dotted line) and RHCW schemes applied to the nonlinear model; **(b)** Time evolution of the window size and estimated window size (dotted line) on nonlinear system.

As discussed in [13], it is possible to show that, for a given positive constant γ , the controller

$$u(t) = Kx(t), \quad (6)$$

with K obtained by solving a further appropriate LMI problem, renders the uncertain time-delay system (5) quadratically stable with an H^∞ norm bound γ . Moreover, as shown in [9], it is possible to design a robust observer for system (5) by resolving an LMI problem. Namely, as discussed in [9], by adapting the theoretical approach in [11], it is possible to show that if $\hat{W}(s) = HX(s)$ is the quantity to be observed and $Y(s)$ is the Laplace transform of the measured output of system (5) then,

$$\begin{aligned} \hat{W} &= H(sI_2 - A - A_d e^{-s\tau} + LC)^{-1} B_d e^{-s\tau} U(s) \\ &+ H(sI_2 - A - A_d e^{-s\tau} + LC)^{-1} L Y(s) \end{aligned} \quad (7)$$

generates a robust estimation of $\hat{W}(s)$, if L is chosen by solving an appropriate LMI problem. In particular it can be shown that the time evolution of the estimation $\hat{W}(t)$ given by (7) satisfies the following conditions:

$$\begin{cases} \lim_{t \rightarrow \infty} (W(t) - \hat{W}(t)) = 0, & \text{for } \Gamma(s) \equiv 0, \\ \|W(t) - \hat{W}(t)\|_2, & \text{is bounded for } \Gamma(s) \neq 0. \end{cases} \quad (8)$$

We consider for the parameter uncertainties in the model (5) the bounds $|N - N_0| \leq \Delta N$, $|R - R_0| \leq \Delta R$ and $|C - C_0| \leq \Delta C$ which can be recast in the appropriate form as required in the controller and observer design. Note that, as for all other AQM control schemes based on the linearized model of the TCP flow, the controller guarantees local stability when applied to the nonlinear TCP fluid model. As detailed in [9], the controller validation in network-simulator and experimentally, shows that the controller presented here performs well when applied to control a realistic TCP connection.

IV. PERFORMANCE EVALUATION

In what follows, the RHC strategy presented above is applied to the fluid flow model of TCP Westwood (shortly RHCW) and tested numerically. For the sake of comparison, the results are contrasted with those produced by using a classical PI-based AQM control scheme in different network scenarios. All the simulations presented here are carried out using Simulink on the network topology introduced in [5]. The parameters of the PI controller are those suggested in [5]. In particular we will validate the effectiveness of RHCW on four different scenarios: 1) $N(t) = N_0$, $R(t) = R_0$ and $C = C_0$, 2) $N(t) = N_0$ and slowly varying $R(t)$, 3) slowly varying $R(t)$ and load $N(t)$.

A. Case 1: $N(t) = N_0$, $R(t) = R_0$ and $C(t) = C_0$

We consider the RHCW and PI performance when: $C = 3750$ packets/s, $R_0 = 0.246$ s, $N = 60$, $q_{max} = 800$ packets, $W_0 = 15$ packets, $q_0 = 200$ packets, $p_0 = 0.02$. Fig. 2(a) shows that the RHCW presents no overshoot and fast convergence to the desired set-point when compared to a PI controller. The online estimation of the window size is observed to be in good agreement with the actual value.

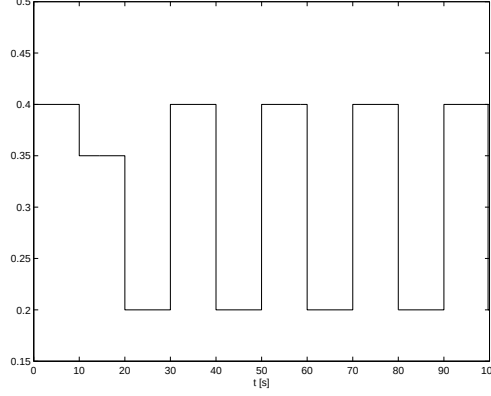


Fig. 3. Case 2: T_p variations

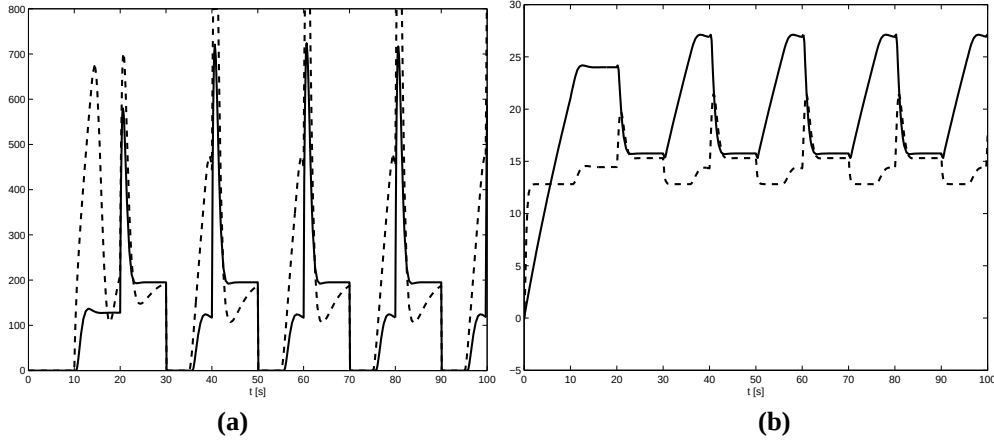


Fig. 4. Case 2: **(a)** Time evolution of the queue length for the PI-AQM (dotted line) and RRHW schemes applied to the nonlinear model; **(b)** Time evolution of the window size and estimated window size (dotted line) on nonlinear system.

B. Case 2: $N(t) = N_0$ and slowly varying $R(t)$

We will consider the case where the round trip propagation delay T_p depicted in Fig. 3 is slowly varying in the interval $(0.19, 0.4)$ corresponding to a typical uncertainty interval about the nominal value of the round trip time in a communication network, also in the absence of strong congestion [12]. The evolution of the queue length for the robust RHCW scheme and the PI controller, depicted in Fig.4(a), shows that the robust RRAQM scheme presents an improved transient and steady-state performance. Namely, the PI controller shows consistent variations of the queue length (between minimum and maxim values) and so of the jitter delay. Moreover, we observe intervals where packets are lost due to queue overflows ($q \geq 800$). The robust RHCW, instead, guarantees an acceptable steady-state response and eliminates all packet losses over the time range of interest while reducing queue variance. The resulting estimation error is bounded as expected from the theory presented in Sec. III.

C. Case 3: slowly varying $R(t)$ and $N(t)$

Now as shown in Fig. 5 larger variations of the round-trip propagation delay ($T_p \in (0.19, 1.2)$) are considered together with load variations (N variable $\in (45, 80)$). We can observe in Fig. 6 that also in this case RHCW performs significantly better than the PI scheme with no packet losses, low queue excursion, better queue utilization and resulting good window estimation.

Similar results are observed when a slow link capacity variation of $C \in (3100, 3750)$ ¹ is added to previous scenario. The variation of such link capacity might represent the reduction of bandwidth advertised from long-lived TCP flow connection due to the presence of background unresponsive traffic flows as UDP and short-lived TCP.

¹the variation in C is obtained by adding a square wave signal (period 30 s, amplitude of 700 packets) to a normal random signal with mean equal to 3750 packet, variance equal to 300 and sample time 0.1.

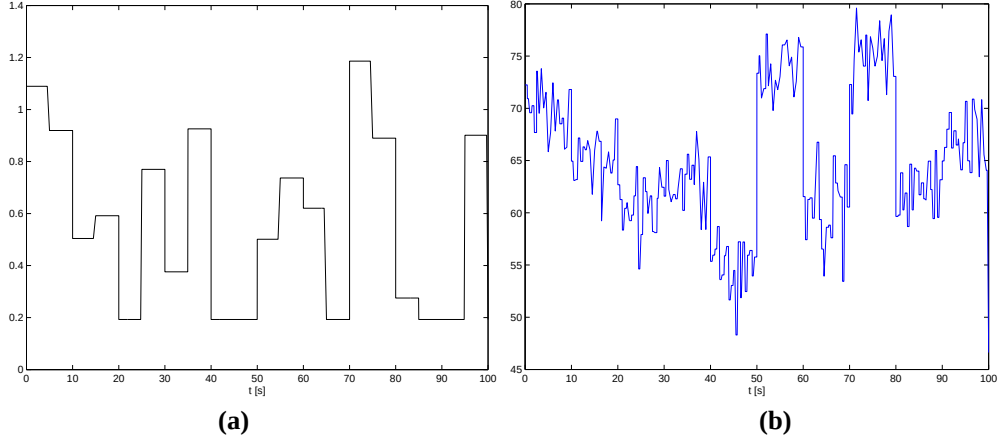


Fig. 5. Case 3: **(a)** T_p variations; **(b)** N variations

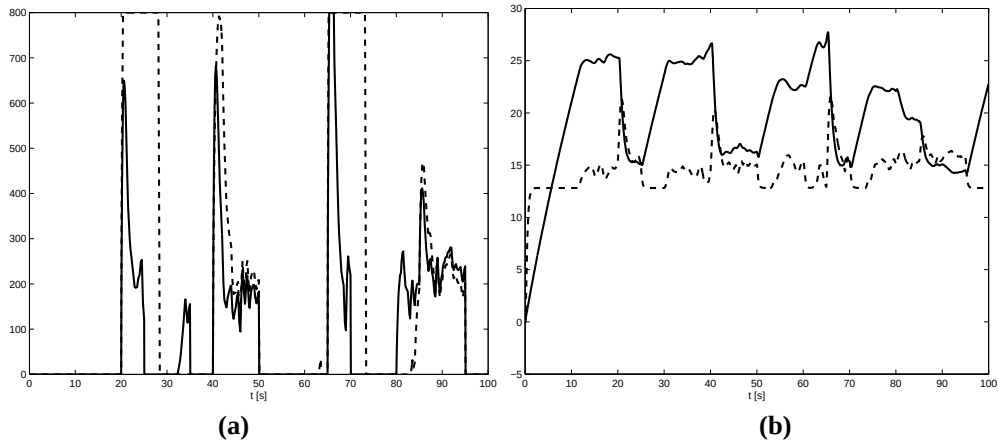


Fig. 6. Case 3: **(a)** Time evolution of the queue length for the PI-AQM (dotted line) and RHCW schemes applied to the nonlinear model; **(b)** Time evolution of the window size and estimated window size (dotted line) on nonlinear system.

V. CONCLUSION

We have discussed the application of a novel robust AQM controller, developed in [9], to networks with Westwood type traffic. The scheme is based on a full state feedback controller which is implemented through the use of a robust observer. It has been shown that such a device provides a good online estimate of the window size that can be successfully used for control purposes. The resulting robust AQM control scheme was validated through numerical simulations showing that it performs better than other schemes such as the one based on a classical PI controller. In particular, the robust AQM scheme is found to guarantee acceptable performance even in the presence of unwanted variations of the load, the round trip time and the link capacity. As, these variations are bound to occur in practice, we anticipate that the use of robust AQM controllers taking explicitly into account the uncertain, time delay nature of the system under investigation is essential to guarantee acceptable network performance under all circumstances.

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