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Design, validation and experimental testing of a robust AQM control

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ABSTRACT

This paper is concerned with the design, the validation and the experimental testing of improved AQM control schemes to cope with unwanted variations of characteristic parameters such as the average round-trip time, the load and link capacity. An appropriate robust H^{∞} controller for time-delay systems is proposed and hence used to design a suitable AQM control scheme. A robust observer is used to estimate the online transmission window resulting in an output feedback stabilization scheme for AQM. The resulting control law is validated and tested firstly through numerical simulations in network simulator (NS-2) and then experimentally.

1. Introduction

A typical information exchange over the Internet is guaranteed by several intermediate nodes (routers) which direct packets originated by the sender to the receiver over links with limited bandwidths. Each router has a finite buffer for storing packets exceeding the total capacity of the link. When the packet net flow exceeds the buffer size the link becomes congested causing a so-called *packet drop* to occur. Namely, the packet is lost and the sender required to transmit it again.

The control mechanism often used to prevent this phenomenon (or at least reduce its occurrence) is the transmission control protocol (TCP) (Jacobson, 1988). During a TCP session, the receiver sends back to the sender an acknowledgment signal for each packet which has been received. In practice, the TCP sender transmits W packets per time unit (W is called window size) and waits for their respective acknowledgments. If packets are acknowledged, the sender then increases W (additive increment), while if a packet is dropped (i.e. not acknowledged by the receiver), W is halved (multiplicative decrement). This mechanism is termed drop-tail. It can be understood as a basic feedback mechanism that drives the sources to transmit at a rate compatible with the network capacity. Notice that here for sake of brevity it omits the description of slow start phase.

Congestion control through drop-tail has several drawbacks. For instance, the reduction of the transmission rate only occurs after packet losses are detected. This typically occurs after some time delay (the round-trip time, RTT), resulting in the queue overflow and further packet losses.

It is becoming increasingly clear that TCP congestion control is not sufficient to provide acceptable performance in terms of the overall quality of service (QoS). So, it has been suggested that feedback strategies more effective than simple drop-tail control mechanisms are required at intermediate routers to complement the endpoint congestion control. Active queue management (AQM) schemes have been proposed in order to deliver preemptively congestion notification to the source for reducing its transmission rate and therefore avoiding buffer overflow. The first aim of AQM schemes is to regulate and stabilize the queue length for efficient resource usage and consistent delay shortening while reducing packet losses. In AQM schemes, a more refined flow control is obtained through a feedback mechanism based on marking[1] (or dropping) packets according to the average queue length. This information when acknowledged by the receiver, allows the transmitter to regulate its transmission rate in accordance with the queue usage. However, AQM schemes can perform poorly in the presence of network parameter variations such as RTT, load and link capacity variations with respect to their nominal values. Such variations are bound to occur in real networks (Blanchini, Lo Cigno, & Tempo, 2002; Larry & Bruce, 2003; Lin, Chen, & Huang, 2008; Manfredi, di Bernardo, & Garofalo, 2004a; Neumann, 2007; Quet & Ozbay, 2004; Yan, Gao, & Ozbay, 2005; Zhang, Towsley, Hollot, & Misra, 2003). Control theory can offer an invaluable set of tools to improve the performance of existing AQM schemes and protocols which can be seen as particular types of feedback control systems (Aweya, Ouelette, & Montuno, 2001; Hollot, Misra, Towsley, & Gong, 2002; Low, Paganini, & Doyle, 2002; Manfredi, di Bernardo, & Garofalo,

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[1] AQM schemes use either packet dropping or marking (explicit congestion notification, ECN mechanism; Ramakrishnam & Floyd, 1999) as congestion notification to the sources. Here, the term ‘marking’ is used to refer to any action taken by the router to notify the source of oncoming congestion.

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2004b; Pan, Altman, & Basar, 1996; Park, Lim, Park, & Choi, 2003; Park, Lim, Basar, & Choi, 2003, Yan et al., 2005).

A particularly cumbersome task when designing AQM control schemes is to guarantee their robustness to uncertain parameters such as the average RTT, the number of active sessions and the link capacity. This paper is concerned with the design of improved AQM control schemes to cope with such unwanted variations. A robust observer is used to estimate, through measurements of the queue and the marking probability, the behavior of the sources in terms of the transmission window W, avoiding its direct measurement as this would be unpractical in applications. An H^{∞} state feedback controller, characterized by a memoryless control law, is used to close the control loop. The resulting control law is validated and tested through numerical simulations in NS-2 and experiments by developed network testbed.

The rest of the paper is outlined as follows. In Section 2, the fluid TCP model used in this paper is described. Then in Section 3, the need for a robust approach is motivated. A robust AQM scheme is then presented in Section 4 and described in Section 5. The resulting control law is validated and tested through numerical simulations on single and multibottleneck scenarios in Sections 6 and 7. Experimental results are reported in Section 8. Finally, conclusions are outlined in Section 9.

2. A fluid model of TCP behavior

A fluid model of TCP dynamical behavior was derived in Misra, Gong, and Towsley (2000) using the theory of stochastic differential equations. The model describes the evolution of the average characteristic variables on the network such as the average TCP window size and the average queue length. Extensive simulations in *network simulator (NS)*-2 (Fall & Varadhan, 2001) have shown that the model captures well the qualitative behavior of TCP traffic flows. Under the assumption of neglecting the TCP timeout, the model is described by the following set of nonlinear coupled ODEs:

$$\dot{W}(t) = \frac{1}{R(t)} - \frac{W(t)}{2}\frac{W(t-R(t))}{R(t-R(t))}p(t-R(t)), \tag{1}$$

$$\dot{q}(t) = \begin{cases} -C + \dfrac{N(t)}{R(t)}W(t), & q>0, \\ \max\{0, -C + \dfrac{N(t)}{R(t)}W(t)\}, & q=0, \end{cases} \tag{2}$$

where W is the average TCP window size (packets), q the average queue length (packets), T_p the propagation delay (s), R the RTT ($R = q/C + T_p$), C the link capacity (packets/s), N the number of TCP sessions and p the probability of a packet being marked. All variables are assumed nonnegative.

If N, R_0 and C are assumed to be the nominal values of $R(t)$, $N(t)$ and $C(t)$, it is possible to linearize the dynamic model (2) about the operating point (W_0, q_0, p_0) where W_0, q_0 are the state values of the equilibrium of interest when the input p is set equal to p_0 (see Hollot et al., 2002 for further details).

$$\begin{aligned} \delta\dot{W}(t) = & -\frac{N}{R_0^2 C}(\delta W(t) + \delta W(t-R_0)) - \frac{1}{R_0^2 C}(\delta q(t) - \delta q(t-R_0)) \\ & -\frac{R_0 C^2}{2N^2}\delta p(t-R_0), \\ \delta\dot{q}(t) = & \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t), \end{aligned} \tag{3}$$

where $\delta W \doteq W - W_0$, $\delta q \doteq q - q_0$ and $\delta p \doteq p - p_0$. Such model has the form of the following time-delay state space system:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= A\mathbf{x}(t) + A_d\mathbf{x}(t-\tau(t)) + B_d u(t-\tau(t)), \\ y &= C_o x(t) \end{aligned} \tag{4}$$

with $x = (\delta W \ \delta q)^{\mathrm{T}}$, $u = \delta p$, $\tau(t) = R_0$, $C_o = (0\,1)$ and

$$A = \begin{pmatrix} -\dfrac{N}{R_0^2 C} & -\dfrac{1}{R_0^2 C} \\ \dfrac{N}{R_0} & -\dfrac{1}{R_0} \end{pmatrix}, \quad A_d = \begin{pmatrix} -\dfrac{N}{R_0^2 C} & \dfrac{1}{R_0^2 C} \\ 0 & 0 \end{pmatrix}, \quad B_d = \begin{pmatrix} -\dfrac{R_0 C^2}{2N^2} \\ 0 \end{pmatrix}. \tag{5}$$

In what follows, for the sake of clarity, the same parameter values considered in Hollot et al. (2002) will be considered, i.e. $C = 3750$ packets/s, $R_0 = 0.246\,$s, $N = 60$ sessions, $q_{max} = 600$ packets corresponding to the steady-state values $W_0 = 15$ packets, $q_0 = 200$ packets, $p_0 = 0.008$. Note that the linear model (3) is valid under some restricting assumptions. In particular: (1) the model captures only the behavior of long-lived TCP connections neglecting slow start and timeout mechanisms; (2) the behavior of different types of sources is not taken into account such as unresponsive flows and different types of TCP connections; (3) nominal fixed values are assumed for the number of connections N, the RTT R and the link capacity C. These can all vary in real networks.

Despite its limitations, the linear model has been successfully used to design effective AQM control schemes (Hollot et al., 2002; Manfredi et al., 2004b, Manfredi, di Bernardo, & Garofalo, 2007; Quet & Ozbay, 2004; Park, Lim, Park, et al., 2003; Yan et al., 2005). Here the main AQM schemes proposed in the literature are considered with the purpose of comparison with the H^{∞} strategy devised in this paper. Note that the details of the AQM schemes that can be found in Athuraliya, Low, Li, and Yin (2001), Aweya et al. (2001), Floyd and Jacobson (1993), Hollot et al. (2002), Kunniyur and Srikant (2002), Kunniyur and Srikant (2001), Lapsley and Low (1999), Low (2000), Low et al. (2002), Misra, Ott, and Baras (2001) and Park, Lim, Park, et al. (2003) are omitted for sake of brevity.

Note that the robust nature of the controller introduced below will compensate the mismatches due to the nonlinear nature of the actual TCP model. Moreover, in the controller design the high frequency dynamics in the model (3) is considered differently from what done in Hollot et al. (2002) where high frequency dynamics are not strictly taken into account.

3. Need for an improved AQM control scheme

As discussed in Section 2, the fluid model of TCP used to synthesize the controllers described above is based on some restricting assumptions. In particular, fixed nominal values of the network parameters are assumed. In this section, the drawbacks of AQM control schemes in the presence of network parameter uncertainties as delays, load variations and link capacity are outlined. For example, in real networks, the RTT can vary with respect to its nominal value. This can be mainly due to the occurrence of congestion phenomena (varying queue delays) and/or the presence of additional sources at different points in the network (causing the variation of the so-called RTT propagation delay). Moreover, rerouting and traffic from additional unresponsive sources can further contribute to variations of the RTT. These effects can be modelled in (3) as variations of an *equivalent RTT* R_{eq} defined as the harmonic mean of the RTTs, R_k, $k = 1, \ldots, N$, of the N TCP flows accessing the network.

Also the assumption of fixed long-lived TCP workload is typically violated in realistic network scenarios. Variations of link capacities advertised from long-lived TCP flows can be caused by unresponsive traffic such as UDP and short-lived TCP flows.

The variations of these parameters strongly affect congestion dynamics of the network, reducing the effectiveness of classical AQM schemes designed for nominal parameter values. In the presence of realistic variations of the network parameters about their nominal values, AQM control schemes can perform poorly both in terms of their stability margins and overall network performance (in terms of number of packet losses, efficient queue regulation and utilization and queuing delay, Manfredi et al., 2004b; Quet & Ozbay, 2004; Zhang et al., 2003) and references therein. Thus, the ultimate aim of AQM control is that of making the system robust against network parameter uncertainties guaranteeing acceptable performance of the queue dynamics but also robustness to parameter variations.

Several attempts have been made to enhance AQM schemes based on classical control strategies. For example, a robust approach developed using the linearized model (3) was independently proposed in Quet and Ozbay (2004). Despite its clear theoretical interest, the method proposed therein can be difficult to implement in practice as it can be computationally demanding.

Recently, a robust control approach (see Manfredi et al., 2007 for further details) based on the use of a reduction method for time-delay system in single bottleneck scenarios was proposed, leading to a control law with memory.

Notice that the proposed robust H^{∞} theoretical synthesis approach results in a memoryless control law that requires no storing additional state variables and sum computation due to the integral implementation differently from the scheme in Manfredi et al. (2007). In this way the complexity of the proposed robust scheme overcomes in terms of both memory and computation requirements the drawback of the scheme presented in Manfredi et al. (2007). This is found more effective for practical applications as assessed by both numerical and experimental validation. Moreover, the scheme proposed here is validated on more extensive simulation scenarios (not only on single bottleneck one as in previous work) and most notably by means of new experimental runs which were reported elsewhere.

It is worth pointing out that, through the use of the observer, other state feedback approaches could be used as well to further improve the performance of the existing schemes. An important constraint to be kept into account is the highly uncertain nature of communications over networks and the practical constraints on the controller implementation. Then, the performance of such a robust AQM control strategy is analyzed in multibottleneck scenarios by NS-2. It is shown that despite their original design on single bottleneck link, they can still guarantee better performance than other more traditional AQM controllers even in the multibottleneck case.

The controller takes explicitly into account the time delayed and uncertain nature of the linearized TCP fluid model introduced in Section 2. Namely, a TCP fluid model is considered with uncertainties and delays of the form:

$$\begin{aligned}\dot{\mathbf{x}}(t) &= (A+\Delta A(t))\mathbf{x}(t) + (A_d+\Delta A_d(t))\mathbf{x}(t-\tau(t)) \\ &\quad + (B_d+\Delta B_d(t))u(t-\tau(t)), \\ y &= C_o x(t), \end{aligned} \tag{6}$$

where $x(t) \in \mathbf{R}^n$ is the state vector, $u(t) \in \mathbf{R}^m$ is the control input and $y(t) \in \mathbf{R}^p$ is the controlled signal output. $\Delta A(t)$, $\Delta A_d(t)$ and $\Delta B_d(t)$ are the uncertainties depending form network parameters uncertainties $|N(t)-N| \leqslant \Delta N$, $|R(t)-R_0| \leqslant \Delta R$ and $|C(t)-C| \leqslant \Delta C$.

4. Control design

The AQM control schemes so far presented above are based on the use of an output feedback control loop. Namely, the control action takes directly into account just the queue length q. To synthesize controllers, guaranteeing higher performance, it would be desirable to design a full state feedback control law. In doing so, the control action would be based not only on the queue length q but also on the window size W. While theoretically possible, in practice it is hard or even impossible to explicitly measure W. Thus, it is proposed that such quantity could be estimated on line by means of an appropriate observer. In particular W can be estimated on the basis of the marking probability $p(t)$ fed into the system and the resulting queue dynamics $q(t)$. From the control viewpoint the major theoretical obstacle is the highly uncertain and noisy nature of communications over the network. Hence, here it is chosen to design a full state feedback control scheme for AQM based on the use of a robust observer.

In doing so, two stages are considered:

(1) A robust observer will be designed to estimate the average transmission window online.
(2) An appropriate robust controller for time-delay systems is synthesized for the linearized TCP fluid model (3).

The resulting control scheme is shown in Fig. 1.

The proposed controller is derived by using a fluid model (3) presented in Hollot et al. (2002), representing the behavior of N homogeneous sources accessing to single bottleneck. Notice that the system of N sources with heterogeneous RTT R_k, $k=1,\dots,N$ on single bottleneck behaves in the mean as a system with N flows each having an identical equivalent RTT $R_{eq} = (1/N)\sum_{k=1}^{N} 1/R_k$ (Hollot, Misra, Towsley, & Gong, 2001). So the controller would still behave reasonably in presence of heterogeneous sources (Hollot et al., 2001) and different network topology (di Bernardo, Garofalo, & Manfredi, 2005; Floyd & Jacobson, 1993) as shown by NS-2 validations in Sections 7 and 8.

5. Robust H^{∞} AQM control (RHC)

To obtain an improved AQM control scheme one should seek to apply an H^{∞} state feedback controller design method to the linearized time-delay model of a TCP connection given by (3). For the sake of clarity, the details of the design methodology are reported in Appendixes A and B, referring the reader for further details. Solving the LMI problem (A.3) for the TCP model in the presence of uncertainties of the load N, the RTT R and link capacity C, a control was chosen of the form $u(t) = Kx(t)$. Notice that, nevertheless, the robust nature of the controller makes the control action effective also in the presence of bounded variations of the RTT due, for example, to variations of the queuing delays. Possible variation of the propagation delay T_p, will be taken into account as uncertainties in the system matrices.

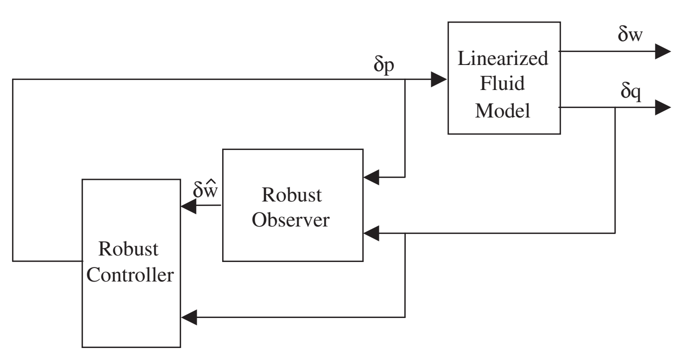

Fig. 1. Block diagram of the proposed robust AQM control scheme.

Having in mind the theoretical approach in Fattouh, Sename, and Dion (2000) presented in Appendix B, it is possible to show that if $\delta\hat{W}(s)$ is the average window size to be observed and $\delta q(s)$ and $\delta p(s)$ are the Laplace transforms of the measured queue length and marking probability, then

$$\delta\hat{W}(s) = \frac{a_1 s + a}{b_2 s^2 + b_1 s + b} e^{-sR_0}\delta p(s) + \frac{c_1 s + c}{b_2 s^2 + b_1 s + b}\delta q(s) \qquad (7)$$

with $L = [l_1 \;\; l_2]^{\mathrm{T}}$, $a_1 = -R_0 C^2/2N^2$, $a = -(C^2/2N^2) - l_2(R_0 C^2/2N^2)$, $b_2 = (1 - (N/R_0 C))$, $b_1 = ((1/R_0) + (2N/R_0^2 C) - (N/R_0 C)l_2 + l_2)$, $b = (2N/R_0^3 C) + (2N/R_0^2 C)l_2 + N/R_0 l_1$, $c_1 = (l_1 - (l_2/R_0 C))$, $c = (1/R_0)l_1$, generates a robust estimation of $\delta\hat{W}(s)$ satisfying (B.3), if L is chosen according to (B.2). Notice that, to derive (7), one has to approximate the time delay e^{-sR_0} in the term $A_d e^{-s\tau}$ in (B.1) as the first-order lag to simplify the final transfer function of the observer.

Note that the arbitrary constants γ and γ_0 required for the synthesis of the controller and the observer, were chosen by trial and error as the minimal feasible values satisfying the given requirements, in order to reduce the effects of uncertainties.

It is considered that the following bounds on the parameter uncertainties in (3) which can be recast in the appropriate form as required in the controller and observer design; namely, $|N(t) - N| \leqslant \Delta N$ with $\Delta N = 240$ sessions, $|R(t) - R_0| \leqslant \Delta R$ with $\Delta R = 0.25$ s and $|C(t) - C| \leqslant \Delta C$ with $\Delta C = 80$ Mb/s.

The AQM robust controller marks packets depending on the actual queue level and estimated windows size. So the marking probability is composed of reactive and predictive terms and it grows with both the increase in measured level of congestion (queue level: packet in queue) and the estimated sources average aggressively (estimated windows size related to packets 'in flight'). 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 will be shown in Sections 6 and 8, the controller validation in network simulator and through experiments, shows that the controller presented here performs well when applied to control a realistic TCP connection.

6. Controller validation through NS-2

This section seeks to validate the effectiveness of the H^∞ AQM controller (shortly labelled as RHC) derived above and compare its performance with respect to other AQM schemes. To this aim, after validating the controller in Simulink, NS-2, was used a network simulator widely used in the control and communication communities (Fall & Varadhan, 2001) which takes into account also the effects of discretization and its nonlinear nature. Simulations, unless otherwise stated, refer to a single bottlenecked router running the AQM scheme connected by a link with a capacity of 15 Mb/s. The propagation delay for the flows is uniformly distributed between 200 and 280 ms. The target queue length q_0 is set to 200 packets while the maximum buffer size is 600. The default transport protocol is TCP-Reno with ECN marking (Ramakrishnam & Floyd, 1999). The control parameters were selected for this network topology in accordance to the guidelines given in the original paper (Athuraliya et al., 2001; Floyd & Jacobson, 1993; Hollot et al., 2002; Kunniyur & Srikant, 2001; Park, Lim, Park, et al., 2003). Notice that the average packet length is set to 1 kbyte differently from the nominal value of 500 bytes used for control design. The aim is to test the AQM robustness controllers with respect to packet size, varying in practice. Indeed in real networks, the packet size is usually chosen depending on the particular application being considered and it is variable (i.e. in the real experiment reported in the paper the average packet size is around 1500 byte). Notice that corresponding to 1 kbyte packet size, the other AQM controllers respect the design rule reported in the original papers yet.

The proposed controller was implemented in NS-2 by a proportional controller with marking probability depending on the estimated windows size and actual queue level. Notice that, to implement the observer time delay, the term e^{-s} in (7) is approximated by a first-order lag to simplify the final transfer function of the observer. The transfer function of the observer has been approximated by a transfer function of lower order which presents the same behavior in the bandwidth of interest. When compared to AQM schemes available in the literature the complexity of the proposed scheme is comparable (or even less) in terms of both memory and computation requirements. This is found more effective for practical applications as assessed by both numerical and experimental validations.

The sampling frequency of the RHC control scheme is $f_s = 160$ Hz as in Hollot et al. (2002). For all other schemes the sampling frequency, such as the rest of unspecified parameters, are fixed to values recommended in the original papers and in NS-2. A variety of numerical simulations and experiments have been reported. Namely, (i) the robustness of RHC to network parameter uncertainties and (ii) its dynamic behavior for different network traffic scenarios have been investigated. Then in Section 7 is shown a validation on multibottleneck scenarios. Finally, in Section 8 is presented some experimental results.

6.1. Robustness to network parameters uncertainties

Beginning with the investigation of the robustness of the AQM scheme in the presence of variations of (i) the load N; (ii) the round-trip propagation delay T_p; (iii) the link capacity C. In particular, the mean and the standard deviation of the queue

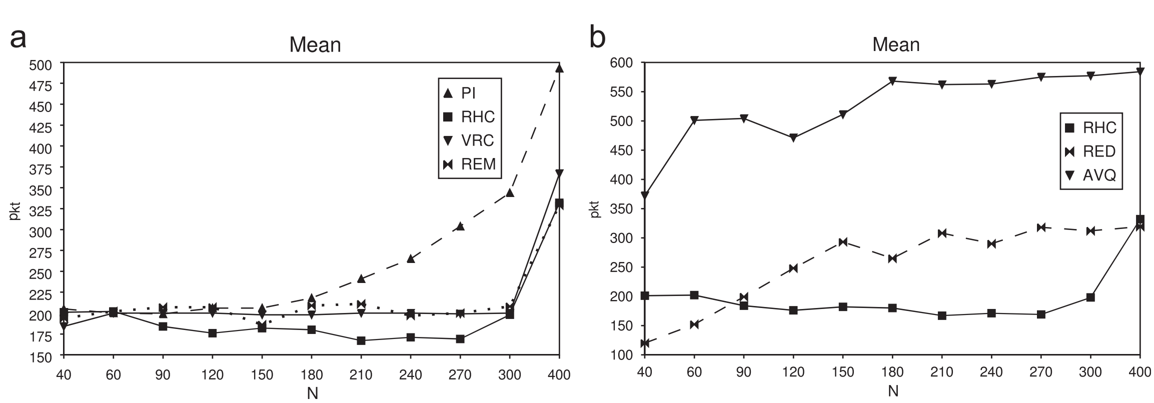

Fig. 2. Mean queue under N variations: (a) PI, RHC, VRC, REM; (b) RHC, RED, AVQ.

length are evaluated in order to assess the control effectiveness to achieve queue stabilization and therefore to reduce queueing and jitter delays. High queue standard deviation implies variable RTT for the sources and also low queue utilization if the queue goes frequently to zero. In order to better evaluate the differences between the standard deviation of the queue length under different control actions, a relatively large queue (buffer size of 600 packets) is chosen.

6.1.1. Robustness to load variations

It is considered that the single bottleneck topology introduced above and repeat the simulation for different values of the load, N, varying from 40 to 400. For each value of the load, the mean value of the queue and its standard deviation under the action of different controllers are recorded. For the sake of clarity, the performance of the new scheme in each of the figure panels is reported. As shown in Figs. 2 and 3, the VRC control scheme guarantees the best set point regulation thanks to its derivative component that causes high variance with queue oscillations for lower values of the load (down to 60). The PI control scheme shows high queue standard deviation for both high and low load levels, while not achieving the desired set point from a medium load value of about 180 sessions. The RHC scheme presented in this paper achieves a good queue stabilization with limited queue oscillations. As expected, RHC does not guarantee perfect set point regulation as it is designed to ensure queue stabilization in the presence of load, RTT and link capacity variations. The set point error is never greater than 20 percent with respect to the target value. The REM scheme shows an acceptable behavior while the queue mean value

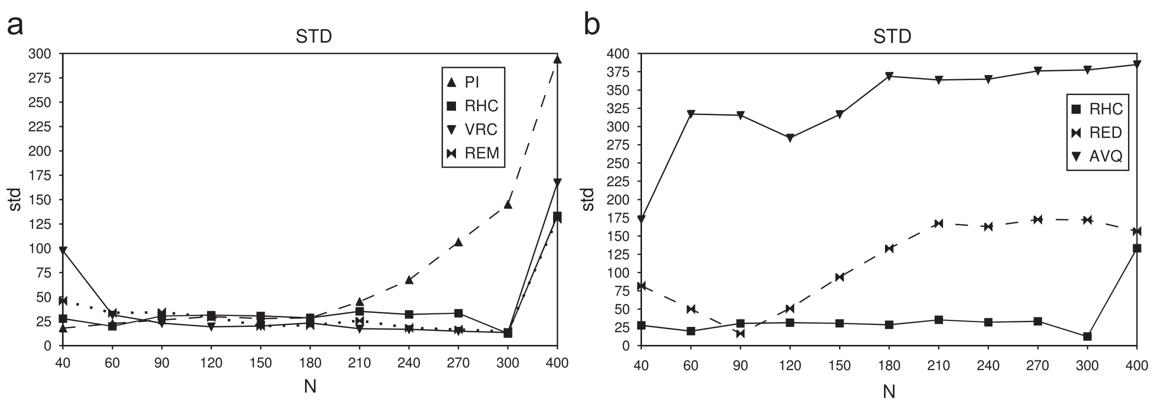

Fig. 3. Queue standard deviation under N variations: (a) PI, RHC, VRC, REM; (b) RHC, RED, AVQ.

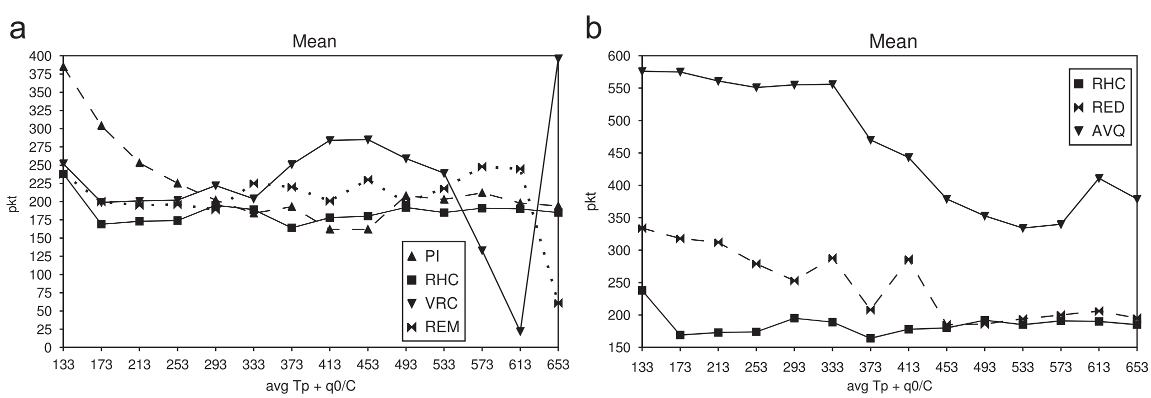

Fig. 4. Mean queue under T_p variations: (a) PI, RHC, VRC, REM; (b) RHC, RED, AVQ.

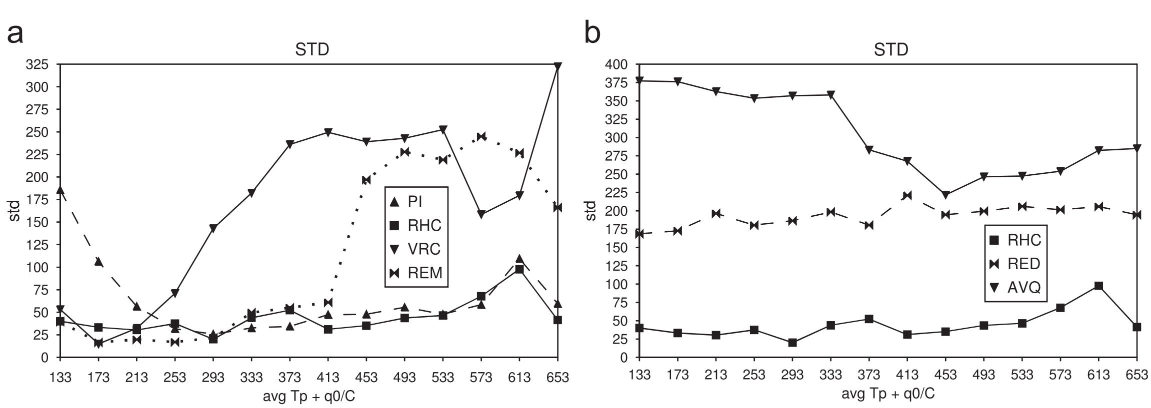

Fig. 5. Queue standard deviation under T_p variations: (a) PI, RHC, VRC, REM; (b) RHC, RED, AVQ.

under RED control is directly dependent upon the load level. Finally, AVQ control performs poorly. As explained in Kunniyur and Srikant (2001), this might be due to the fact that this control strategy is particularly suited for the case of short queue lengths.

6.1.2. Robustness to variations of the round-trip propagation delay

Keeping the same topology introduced above, variations of the average round-trip propagation delay between 133 and 654 ms are now considered. In order to guarantee a full queue for increasing delays, a value of the load, $N = 270$, higher than the nominal value is chosen. This also allows testing the controllers in the presence of aggressive sources when the delay is relatively small. In Figs. 4 and 5, the queue statistics are reported as a function of the one-way delay obtained by adding the average propagation delay T_p to q_0/C. In this situation, the RHC scheme shows the best performance when compared with other controllers. In particular, as expected, the VRC controller shows a poor set point regulation and high standard deviation, while the PI controller performs poorly for smaller values of the delay. Also, the mean queue length when the RED controller is active shows an inverse dependence upon the delay variation while the performance of the AVQ scheme improves for increasing delays.

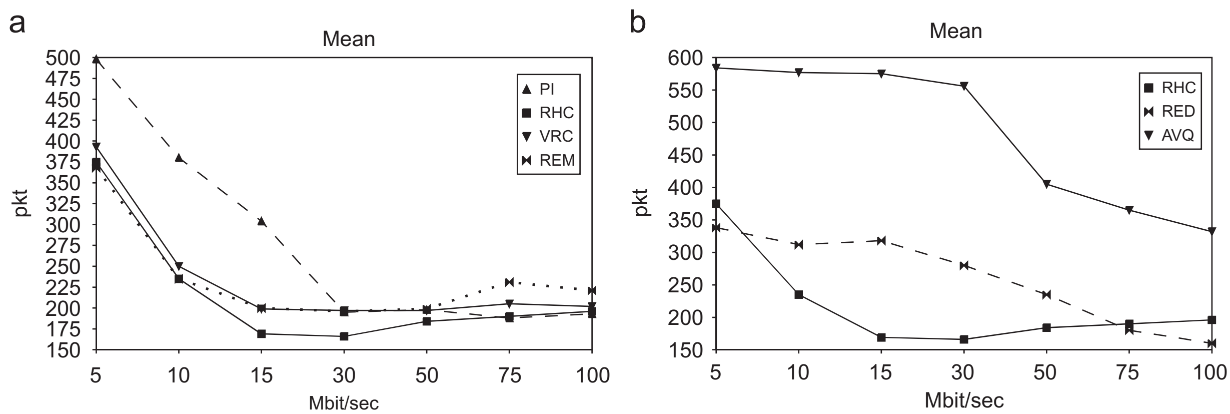

Fig. 6. Mean queue under C variations: (a) PI, RHC, VRC, REM; (b) RHC, RED, AVQ.

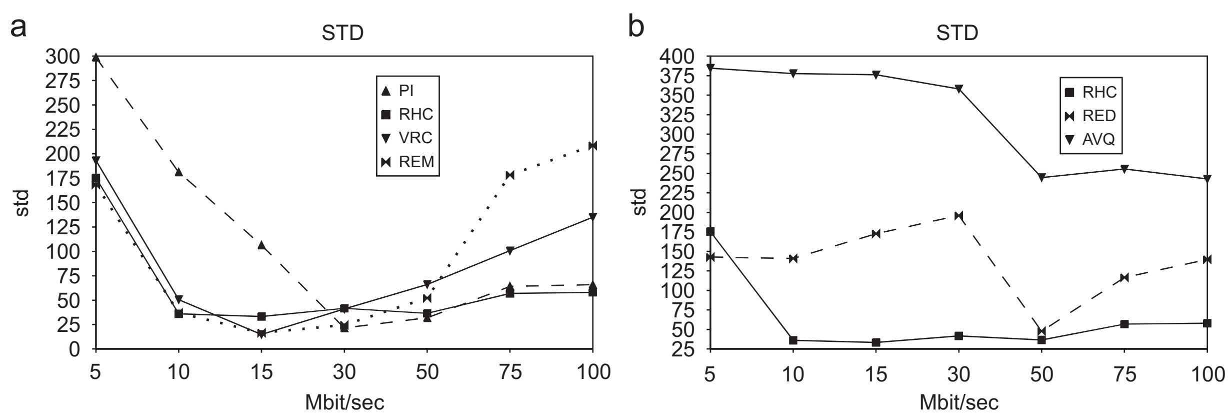

Fig. 7. Queue standard deviation under C variations: (a) PI, RHC, VRC, REM; (b) RHC, RED, AVQ.

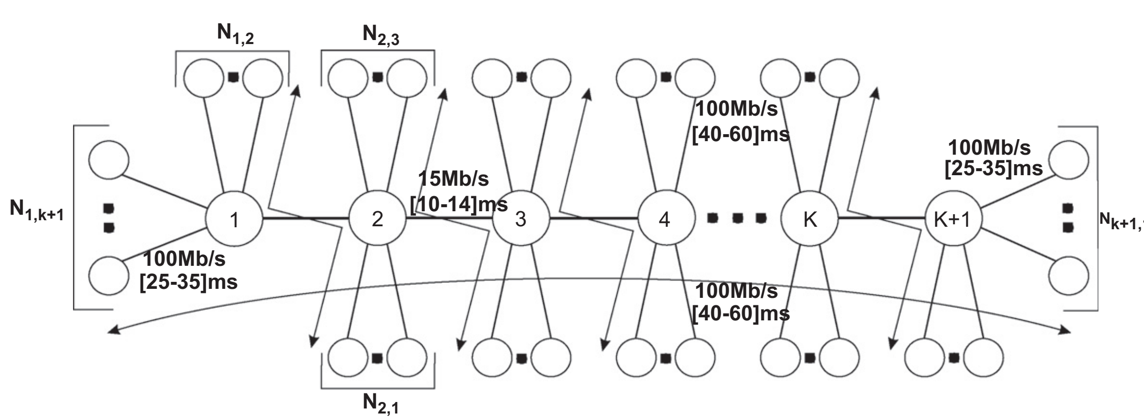

Fig. 8. Multibottleneck topology.

6.1.3. *Robustness to bottleneck link capacity variations*

The ability of the robust controller to cope with variations of the link capacity will now be tested. Repeating the simulation for different values of the link capacity, *C*, varying from 5 to 100 Mb/s.

In this case the RHC and VRC controllers present the best performances in terms of queue statistics as shown in Figs. 6 and 7. Notice that, despite maintaining a similar queue mean value under capacity variations, the RHC guarantees a lower standard deviation of the queue over the range of interest.

Hence, the numerical analysis confirms that, when compared to other existing schemes, the RHC strategy guarantees the best regulation performance in the presence of unwanted delays, load and link capacity variations.

Table 1
Dynamic load *N* and round-trip time *R* variations

Time interval (s)	$R = q_0/C + T_p$ (s)	Time interval (s)	N
0–10	[0.306–0.386]	0–5	60
10–15	[0.266–0.346]	5–15	90
15–20	[0.386–0.466]	15–30	140
20–30	[0.266–0.346]	30–50	50
30–40	[0.173–0.306]	50–60	120
40–60	[0.266–0.346]	60–70	90
60–80	[0.413–0.493]	70–85	180
80–100	[0.226–0.306]	85–100	80

7. Controller validation on multibottleneck scenarios

This section shall seek to validate the effectiveness of the RHC described above and compare its performance with respect to standard AQMs schemes in classical multibottleneck scenarios (Kantawala & Turner, 2002; Yan et al., 2005). Simulation, refer to the general multibottleneck topology router using five level bottleneck topology ($k = 5$) as depicted in Fig. 8. The capacity and propagation delay of each link between routers is set to 15 Mb/s and 10–14 ms, respectively, while the links between routers and vertical crossing senders/receivers ($N_{h,h+1}$, $h : 1, \ldots, 5$)

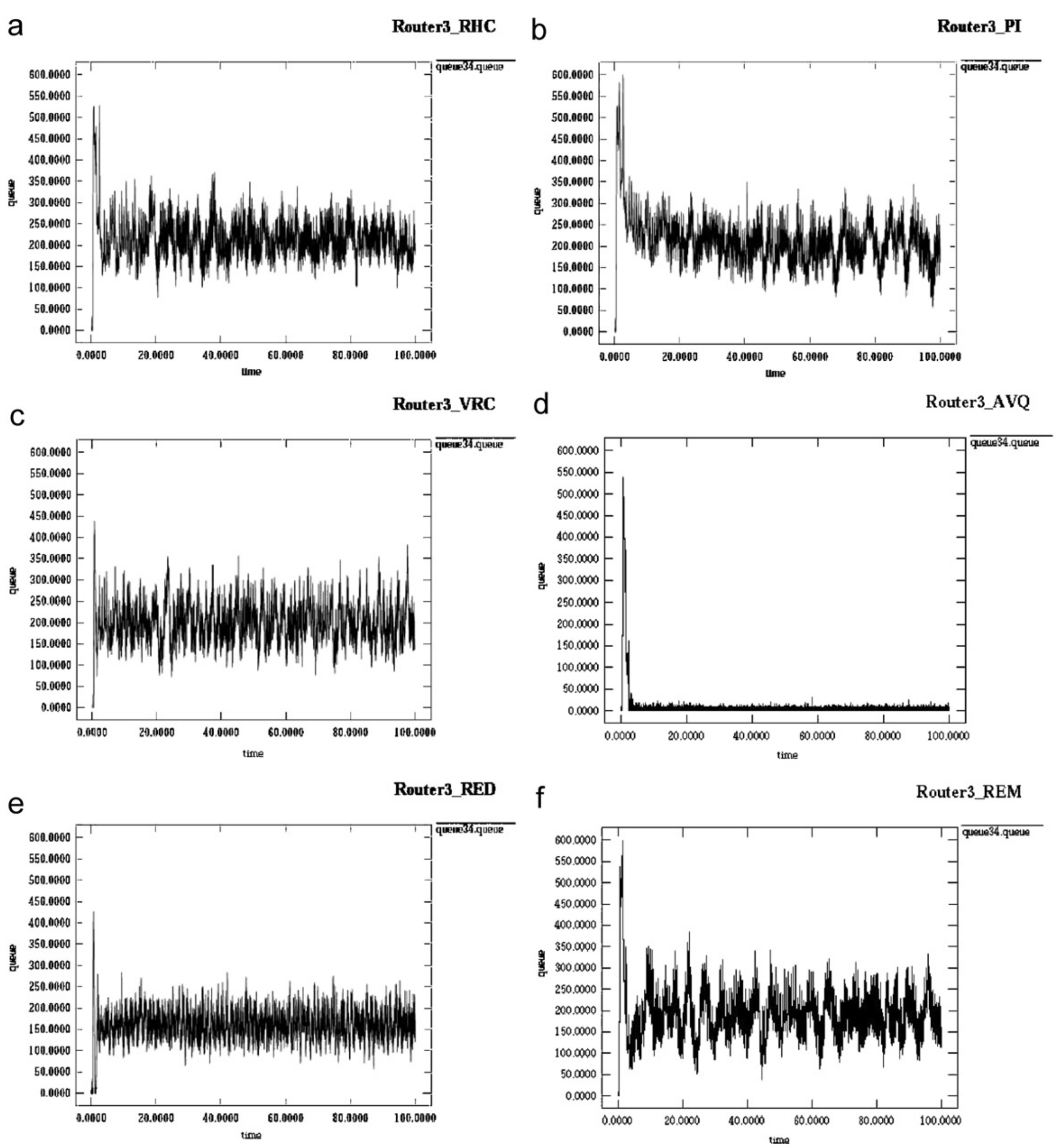

Fig. 9. Multibottleneck topology—packet size 1 kbyte. Time evolution of the queue length: (a) RHC; (b) PI; (c) VRC; (d) AVQ; (e) RED; (f) REM.

have a capacity of 100BaseT rate (100 Mb/s) and a propagation delay of 40–60 ms. There are $N_{1,k+1}$ flows traversing all links. The nominal conditions include all of the N flows set to 30. Notice that differently to previous multibottleneck test topologies the presence of cross-traffic flows $N_{k+1,1}$ (inverse to $N_{1,k+1}$) is also introduced. Indeed this traffic affects heavily the acknowledgment traffic (delaying and/or eliminating it from the network). This can be seen as uncertainty on the RTT. The packet size is set to 1 kbyte. A variety of numerical simulations are reported below. Namely, (i) the nominal case with different packet size and cross traffic; (ii) the robustness of AQM controllers to network dynamic parameter uncertainties (load and RTT) and (iii) the dynamic behavior in the presence of UDP flows and cross traffic are investigated. Notice that cross traffic is related to the effect to add variance to the RTT by causing ACKs to suffer queuing delay.

7.1. Nominal case with different packet size and cross traffic

AQM controllers upon the topology described above were validated when the packet size is fixed to the value of 1000 bytes (differently to the nominal 500 bytes) as further validation of

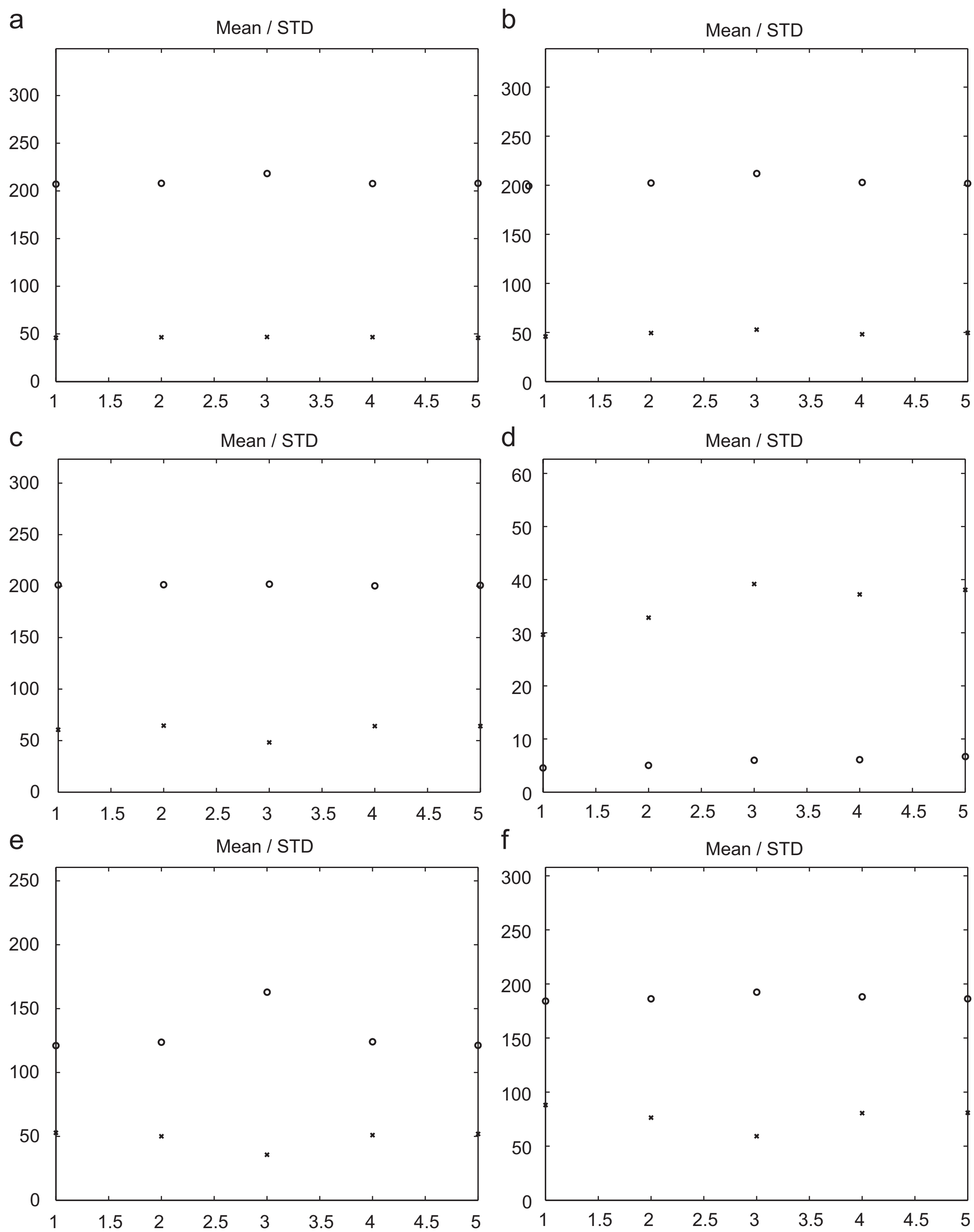

Fig. 10. Multibottleneck topology—packet size 1 kbyte. Mean (○) and standard deviation (×) of the queues at the router k ($k = 1, 2, \dots, 5$) under different packet size: (a) RHC; (b) PI; (c) VRC; (d) AVQ; (e) RED; (f) REM.

AQM controllers upon different packet size. The different packet size from the model point of view corresponds to a different operating point of the network. Then the presence of inverse cross traffic $N_{k+1,1}$, $k = 5$, is considered that corresponds to dynamic queue delays (and so RTT) variations. In Figs. 9 and 10 the queue length and its first-order statistics are shown under AQM controllers. In particular RHC gives overall good set point regulation (mean of the queues approximately near to 200 packets), lower queue standard deviation and faster time response at all routers with respect to other controllers.

7.2. Random TCP connections and RTT variations

Now variations of the round-trip propagation delay are considered together with load variations representing a strong congestion scenario as in Table 1.

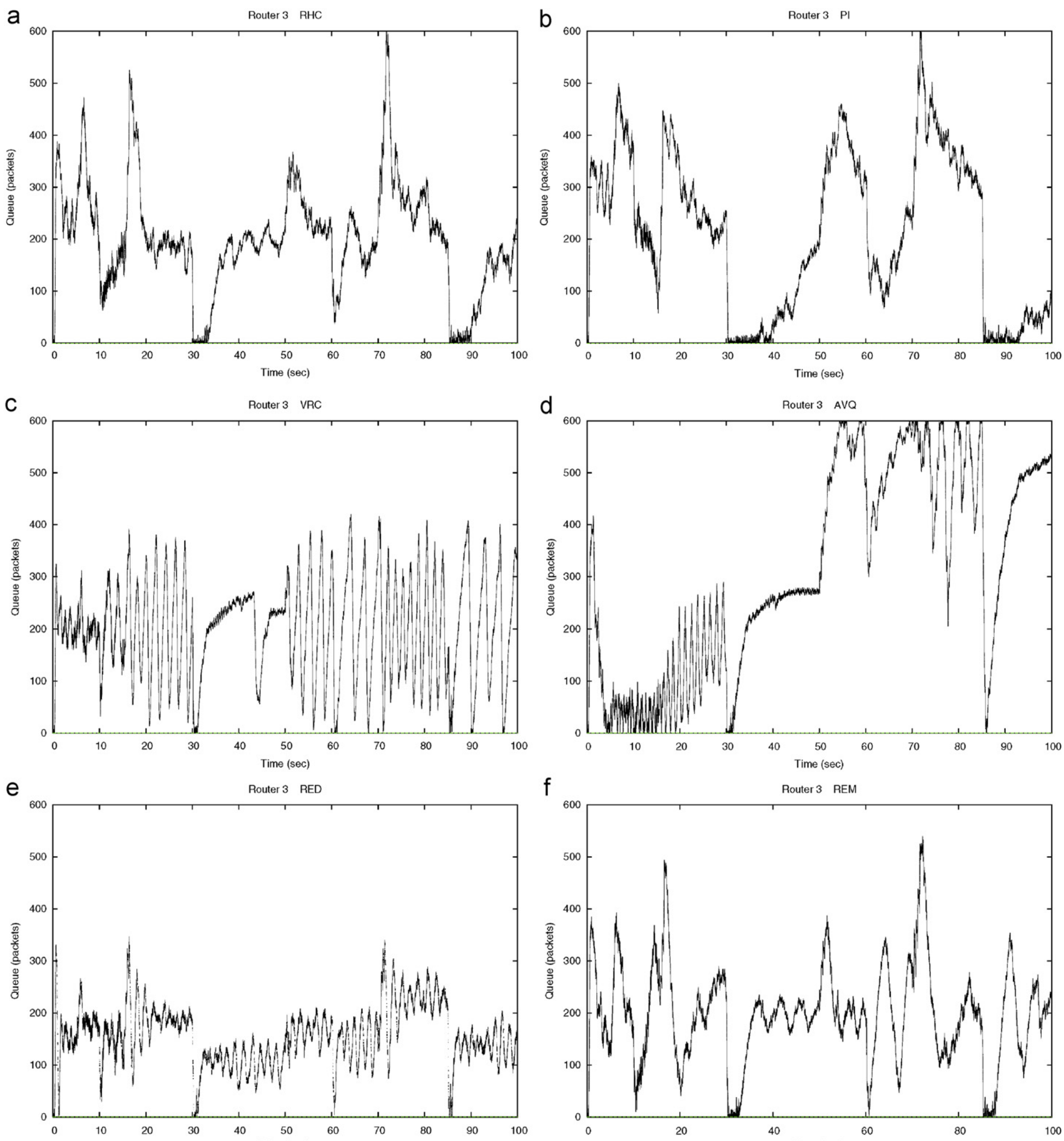

Fig. 11. Multibottleneck topology—N and R variations as in Table 2. Time evolution of the queue length: (a) RHC; (b) PI; (c) VRC; (d) AVQ; (e) RED; (f) REM.

It can be seen that in Fig. 11 that also in this case the robust controller deal with dynamic uncertainties in the load and RTT bounding the queue oscillations (and so packet dropping and queue under utilization). In particular RHC has better and faster set point regulation with respect to PI controller.

7.3. Dynamic behavior in presence of UDP flows and cross traffic

The presence of UDP traffic dynamic not only causes load and RTT variations, but also an equivalent capacity reduction perceived by TCP flows. In particular, studying the effects of adding UDP flows (500 kbyte/s—*CBR*—constant bit rate) to nominal traffic that are switched on at $t = 50$ s and turned off when $t = 100$ s. The presence of inverse cross traffic $N_{6,1}$ is also considered. For sake of brevity only the performance comparison between RHC and PI controllers at the different routers is shown because other AQM schemes presented worse behavior. Notice that in Fig. 13 the faster response time of the RHC and better UDP traffic rejection (by reducing its propagation through bottleneck levels) with respect to PI scheme (Fig. 12). This reduces packet

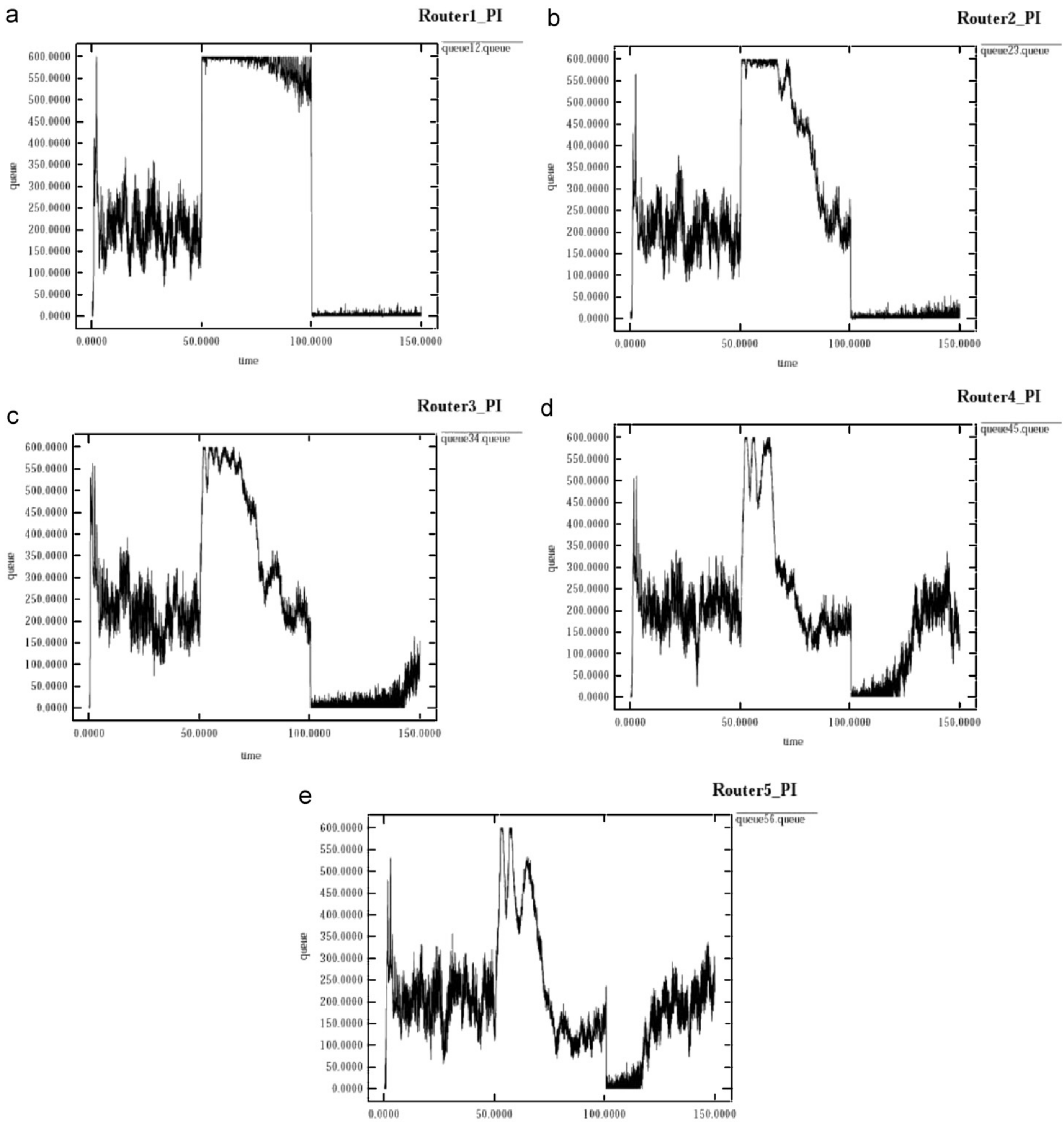

Fig. 12. Time evolution of queue length under PI controller in presence of UDP flow and cross traffic (ecn): (a) Router 1; (b) Router 2; (c) Router 3; (d) Router 4; (e) Router 5.

dropping and queue under utilization while improving set point regulation.

8. Experiments

Some of the control strategies presented above were tested and validated experimentally. In particular, the behavior of RHC, PI and RED AQM controllers are compared when applied to a single bottleneck scenario with $N = 60$ TCP flow, $T_p = 0.240\,\mathrm{s}$ and a capacity $C = 10\,\mathrm{Mb/s}$. The mean dimension of each packet is 1500 bytes and the transport protocol is based on packet dropping. In the experiments, the controllers are implemented by using *FreeBSD* 4.7 operating system. For flow generations, the *netperf* and *iperf* routines were used. Destination and source hosts are Linux based. Notice that, rather than presenting an exhaustive experimental validation, the aim of this section is to provide a preliminary experimental testing of its performance. Further simulations and experiments will be reported elsewhere for sake of brevity. In Fig. 14, the closed-loop queue evolution is reported

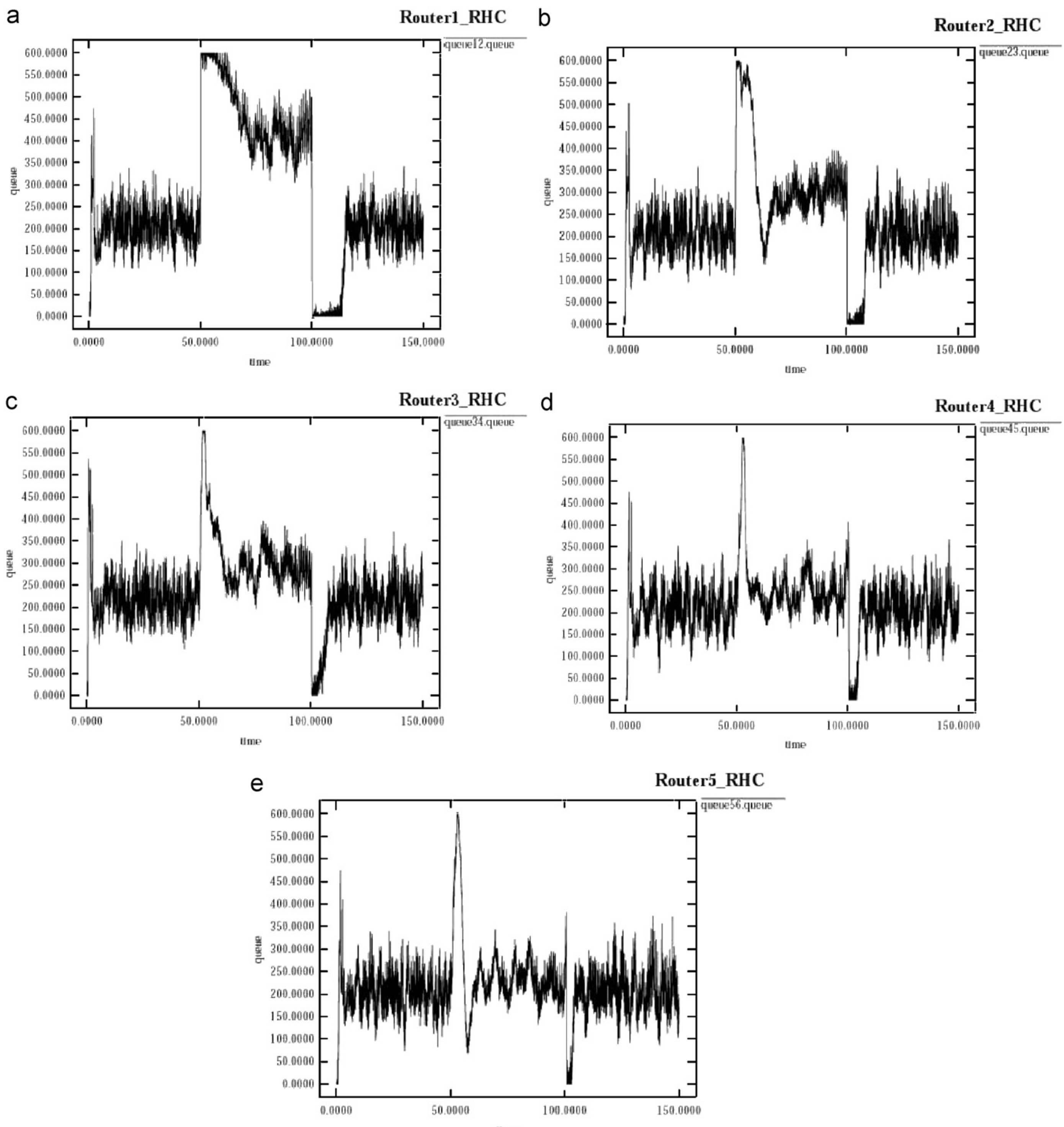

Fig. 13. Time evolution of queue length under RHC controller in presence of UDP flow and cross traffic: (a) Router 1; (b) Router 2; (c) Router 3; (d) Router 4; (e) Router 5.

under the action of PI, RED and RHC schemes. Notice that RHC guarantees a good set point regulation with less oscillations and packet losses, and a faster time response when compared to the dynamics of PI and RED based schemes. In particular, Notice that the RED-AQM strategy fails to guarantee the desired set point regulation. The benefits of the RHC scheme are further confirmed when testing the AQM controllers for higher variations of the RTT with respect to its nominal value as shown in Fig. 15. Finally, variations of the load N according to the schedule in Table 2 are considered.

As shown in Fig. 16, even in this case RHC control achieves a better set point regulation when compared to other schemes and is effective in reducing queue oscillations. Another advantage is the reduced number of packet losses that can be observed under RHC.

Notice that in the experiments dropping mechanism is used. Better performances of RHC is expected if ECN is used to mark packets instead of dropping them obtaining full benefits of the presented AQM scheme, as predicted by NS-2 simulations.

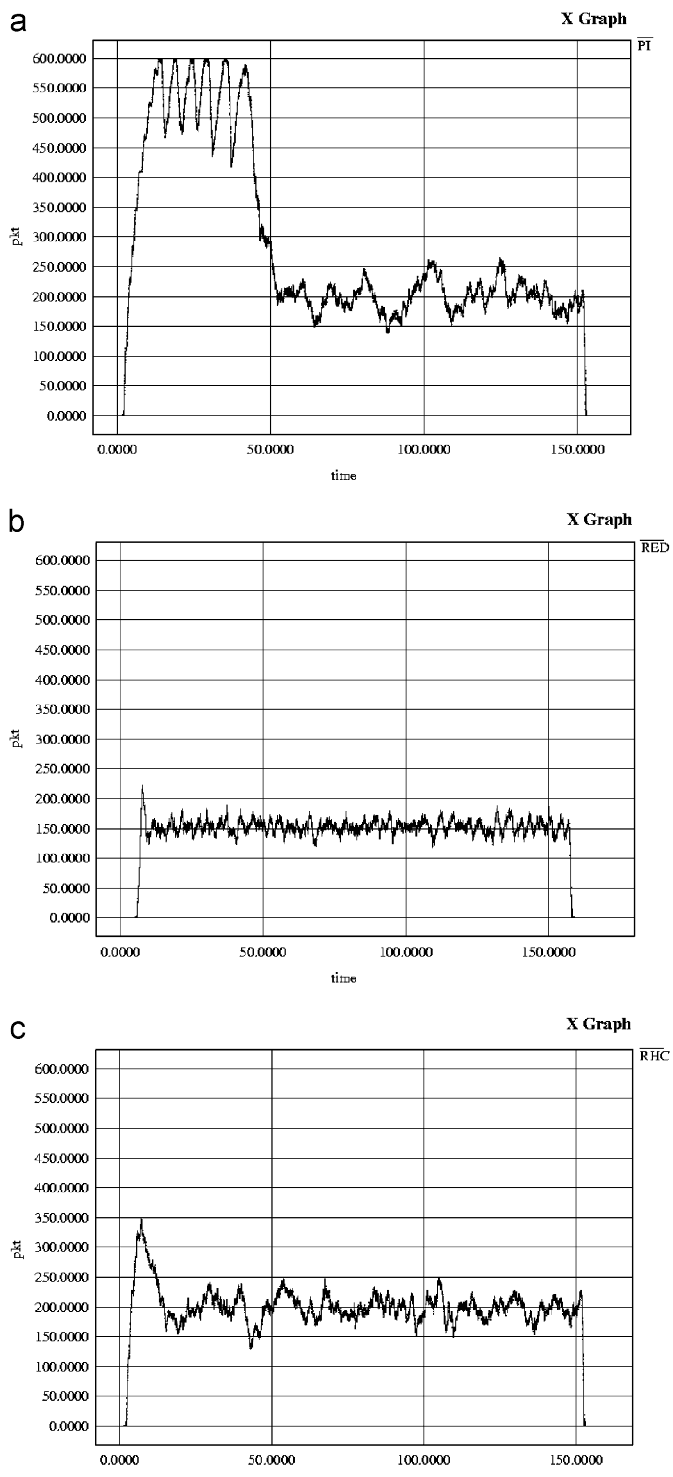

Fig. 14. Experiment: $N = 60$, RTT = 0.240 s. Time evolution of the queue length: (a) PI; (b) RED; (c) RHC.

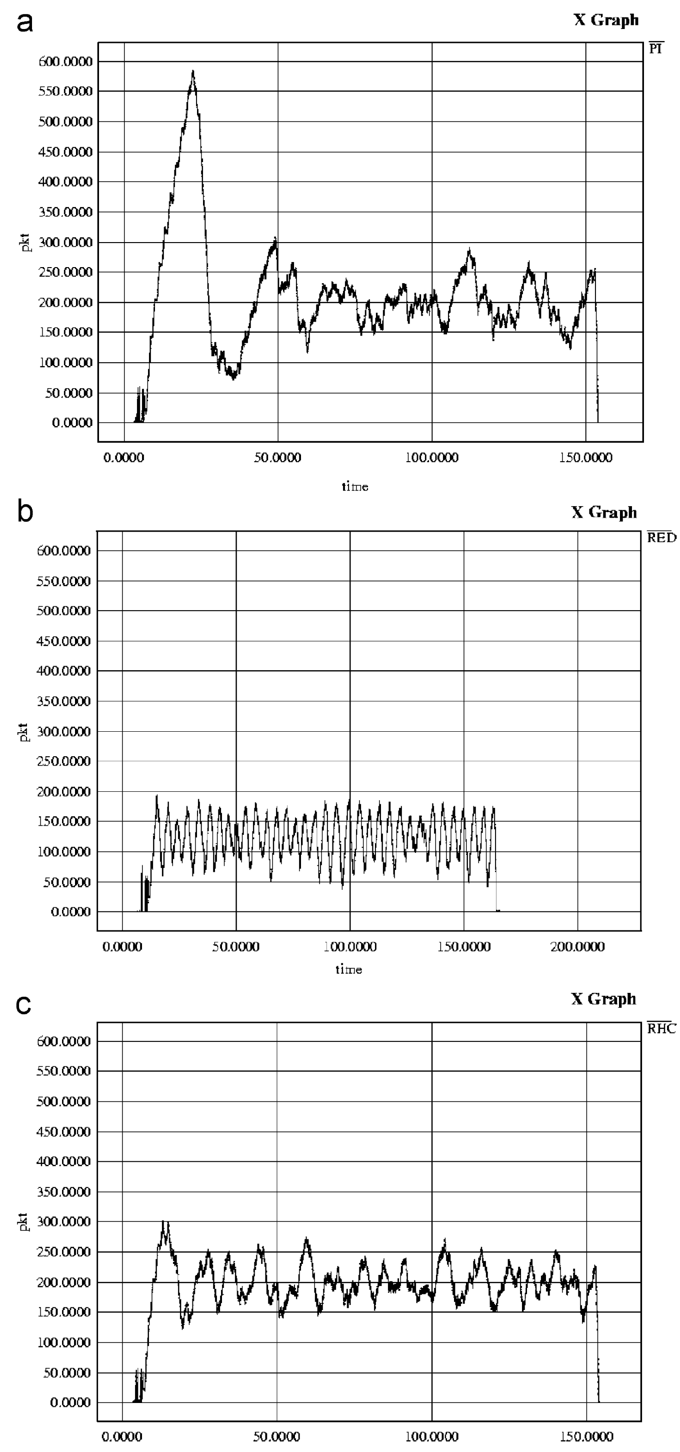

Fig. 15. Experiment: $N = 180$, RTT = 0.500 s. Time evolution of the queue length: (a) PI; (b) RED; (c) RHC.

Table 2
Dynamic load N variations

Time interval, t (s)	N
0–20	60
20–60	90
60–120	40
120–180	160
180–250	60

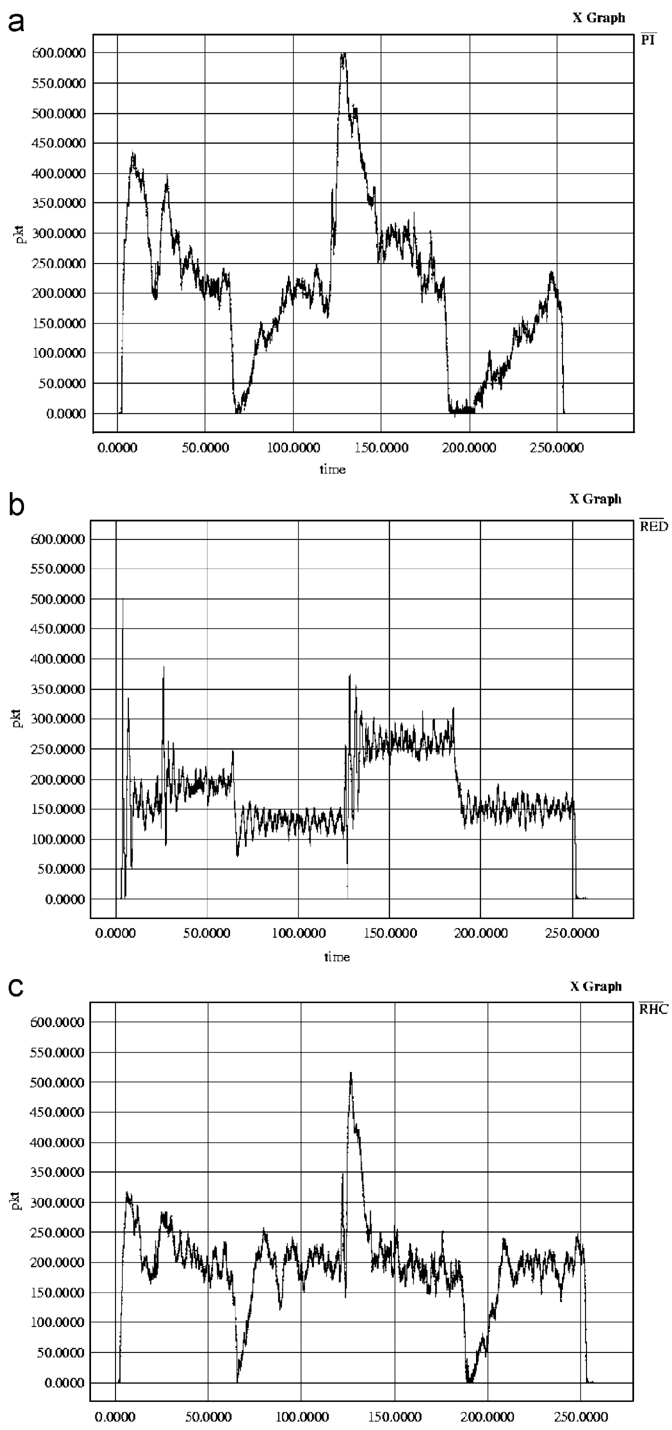

Fig. 16. Experiment: dynamic load variations in Table 2. Time evolution of the queue length: (a) PI; (b) RED; (c) RHC.

9. Conclusions

It has been discussed the design of improved active queue management (AQM) control schemes to address the issue of variations of the network parameters unavoidable in practical applications. An output robust feedback controller was synthesized which takes explicitly into account the uncertain, time-delay nature of the system under investigation. The control synthesis was carried out on a linearized fluid model of a TCP connection often used in the literature. The strategy was shown to be particularly effective on realistic network models through extensive simulations in network simulator and experiments. The performance of the AQM scheme was studied in detail and compared with other AQM control strategies recently presented in the literature. It was shown that the robust algorithm for AQM introduced in this paper is effective to maintain queue stabilization in the presence of variations of the round-trip time, the load and the link capacity. The scheme was tested on a variety of network topologies and shown to reduce, in general, the number of packet losses and dampen the oscillatory queue dynamics.

Appendix A. H^∞ state feedback control

The design of a robust H^∞ state feedback controller for continuous time systems with time-varying delays was recently discussed in Kim and Park (1999). The resulting controller was shown to guarantee quadratic stability of the closed loop system and acceptable error bounds. Moreover, the design can be easily extended to the case of time-delay systems with uncertain parameters.

In particular, it is possible to design a robust feedback controller for system (6) under the assumption that all states are measurable and the time-varying delay $\tau(t)$ satisfies the conditions:

$$0 \leqslant \tau(t) < \infty, \qquad \dot{\tau}(t) \leqslant \beta < 1. \tag{A.1}$$

Moreover, it is supposed that the matrices representing uncertainties in (6) can be expressed as $\Delta A(t) = H_\Delta F(t) E_\Delta$, $\Delta A_d(t) = H_\Delta F(t) \bar{E}_\Delta$ and $\Delta B_d(t) = H_\Delta F(t) E_{u\Delta}$ where H_Δ, E_Δ, $\bar{E}_\Delta$ and $E_{u\Delta}$ are appropriate matrices, and $F(t)$ is such that $F(t) : F(t)^{\mathrm{T}} F(t) \leqslant I$ with its elements being Lebesgue measurable. Under these assumptions, it is possible to show that, for a given positive constant γ, the controller

$$u(t) = Kx(t), \tag{A.2}$$

renders the uncertain time-delay system (6) quadratically stable with an H^∞-norm error bound γ if there exist positive definite matrices Q, S_1, S_2, a positive constant λ and a matrix M such that

$$\begin{bmatrix} U_1 & \gamma\lambda H_\Delta & U_2 & M^{\mathrm{T}} & Q \\ (\gamma\lambda H_\Delta)^{\mathrm{T}} & -\gamma^2 I & 0 & 0 & 0 \\ U_2^{\mathrm{T}} & 0 & -I & 0 & 0 \\ M & 0 & 0 & -S_2 & 0 \\ Q & 0 & 0 & 0 & -S_1 \end{bmatrix} < 0, \tag{A.3}$$

where

$$\begin{aligned} U_1 &= QA^{\mathrm{T}} + AQ + (1-\beta)^{-1} A_d S_1 A_d^{\mathrm{T}} + (1-\beta)^{-1} B_d S_2 B_d^{\mathrm{T}}, \\ U_2 &= QC_o^{\mathrm{T}} + (1-\beta)^{-1} A_d S_1 \bar{C}_d^{\mathrm{T}} + (1-\beta)^{-1} B_d S_2 \bar{D}_d^{\mathrm{T}}, \\ U_3 &= -I + (1-\beta)^{-1} \bar{C}_d S_1 \bar{C}_d^{\mathrm{T}} + (1-\beta)^{-1} \bar{D}_d S_2 \bar{D}_d^{\mathrm{T}}, \\ \bar{C} &= \left[C_o \ \ \frac{1}{\lambda} E_\Delta \right]^{\mathrm{T}}; \quad \bar{C}_d = \left[0 \ \ \frac{1}{\lambda} \bar{E}_\Delta \right]^{\mathrm{T}}; \quad \bar{D}_d = \left[0 \ \ \frac{1}{\lambda} E_{u\Delta} \right]^{\mathrm{T}}, \\ M &= KP^{-1}, \\ Q &= P^{-1}, \\ S_i &= R_i^{-1}, \quad i = 1, 2. \end{aligned} \tag{A.4}$$

Note that the controller gains K in (A.2) can be computed by using the relationship $M = KP^{-1}$ in (A.4) after solving the LMI problem (A.3) with respect to Q, S_1, S_2 and M (see Kim & Park, 1999 for further details).

Appendix B. Robust observer for time-delay systems

The control law discussed above requires full availability of the system states for feedback purposes. To avoid the need for full state feedback it was proposed that the control law be equipped with an appropriate robust observer for time-delay systems. In what follows, the results presented in Fattouh et al. (2000) are adapted to the case of interest.

The design uses a linear matrix inequality approach in order to guarantee the stability of the observer and reduce the effect of model uncertainties on the estimated state. Let $G(s) = C_o(sI_n - A - A_d e^{-s\tau})^{-1} B_d e^{-s\tau}$ be the transfer function representation of system (4). Say $\tilde{G}(s,z) = G(s,z) + \Gamma(s)\Delta(s,z)$ the transfer function of the system under the effect of additive uncertainties of the form $\Gamma(s)\Delta(s,z)$ with $z = e^{-s\tau}$; $\Gamma(s)$ being a fixed stable weighting transfer function matrix and $\Delta(s,z)$ a variable stable transfer function with $\|\Delta(s,z)\|_\infty \leqslant 1$. As discussed in Fattouh et al. (2000), it is possible to show that if $Z(s) = HX(s)$ is the quantity to be observed then,

$$\begin{aligned}\hat{Z}(s) = {} & H(sI_2 - A - A_d e^{-s\tau} + LC_o)^{-1} B_d e^{-s\tau} U(s) \\ & + H(sI_n - A - A_d e^{-s\tau} + LC_o)^{-1} LY(s)\end{aligned} \tag{B.1}$$

generates a robust estimation of $Z(s)$ if, given a scalar $\gamma_o > 0$, there exist a matrix $S \in \mathbf{R}^{n\times r}$ and two symmetric positive definite matrices P and R such that

$$\begin{bmatrix} M & PA_d & 0 & 0 & S\bar{D} \\ A_d^{\mathrm{T}}P & -\bar{R} & 0 & 0 & 0 \\ 0 & 0 & -\bar{R} & 0 & 0 \\ 0 & 0 & 0 & -I_r & 0 \\ \bar{D}S^{\mathrm{T}} & 0 & 0 & 0 & -I_r \end{bmatrix} < 0,$$

where $M = A_0^{\mathrm{T}}P + PA_0 + R + \frac{1}{\gamma_o^2}H^{\mathrm{T}}H - SC_o - C_o^{\mathrm{T}}S^{\mathrm{T}}$, $\bar{R} = \frac{1}{2}R$, $\bar{D} = \|\Gamma(s)\|_\infty$. $Y(s)$ is the Laplace transform of the measured output of system (6) and

$$L = P^{-1}S. \tag{B.2}$$

In particular it can be shown that the time evolution of the estimation $\hat{z}(t)$ given by (B.1) satisfies the following conditions:

$$\begin{cases} \lim_{t\to\infty}(z(t) - \hat{z}(t)) = 0 & \text{for } \Gamma(s) \equiv 0, \\ \|z(t) - \hat{z}(t)\|_2 & \text{is bounded for } \Gamma(s) \neq 0. \end{cases} \tag{B.3}$$

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