Proceedings of the
44th IEEE Conference on Decision and Control, and
the European Control Conference 2005
Seville, Spain, December 12-15, 2005

Performance of Robust AQM controllers in multibottleneck scenarios

Mario di Bernardo*, Franco Garofalo and Sabato Manfredi**

Abstract— **Recently, novel robust AQM congestion control strategies for time delay systems have been proposed. These are based on the use of robust reduction methods and H$^\infty$ strategies resulting in memory and memoryless control laws respectively have been proposed. Their design was carried out on a single bottleneck topology for guaranteeing robust local stability in the presence of network uncertainties in terms of average round-trip time, load and the link capacity. Here we analyze the performance of such robust AQM control strategies on multibottleneck scenarios by NS-2. We will show that despite their original design on single bottle- neck link, they can still guarantee better performance than other more traditional AQM controllers even in the multibottleneck case.**

I. Background

Recently, AQM congestion control strategies have been proposed to improve the performance of standard algorithms (i.e drop tail, red). It has been shown that control theory can offer an invaluable set of tools to improve the performance of existing AQM schemes which can be seen as particular types of feedback control systems [1], [2], [4], [5], [6], [7].

Nevertheless, classical AQM schemes perform poorly in the presence of network parameter variations such as round-trip time, load and link capacity variations which are bound to occur in more realistic networks [6], [7].

Indeed in more realistic networks, the round-trip time (RTT) can also vary with respect to its nominal value because of congestion phenomena and other effects such as the presence of variations of responsive sources at different points in the network (causing the variation of equivalent round trip time propagation delay), rerouting and additional unresponsive source traffic. Also, the assumption of fixed long-lived TCP workload, often taken in the derivation of these models, is 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.

To overcome these problems, robust control approaches have been recently presented in the literature [11], [12], [13], [14]. Recently, novel approaches were introduced in [6], [8], [9] to design robust AQM control strategies. AQM congestion control strategies for time-delay systems have been proposed, which are based on the use of robust reduction methods and H$^\infty$ strategies resulting in memory and memoryless control laws. These controllers were shown to be able to cope with unwanted variations of characteristic parameters such as the the average round-trip time, the load and the link capacity. Their design was carried out on a single bottleneck topology for guaranteeing robust local stability in the presence of network uncertainties in terms of average round-trip time, load and the link capacity. Their effectiveness was shown both by NS-2 and experiments.

The aim of this paper is to analyze the performance of such robust AQM control strategies on multibottleneck scenarios. For this purpose a novel set of experiments will be carried out by NS-2. We will show that despite their original design on a single bottleneck links, the robust control approaches followed in the paper can still guarantee better performance than other more traditional AQM controllers even in the multibottleneck case. It will be shown that the memoryless H$^\infty$ controller performs better than the one based on the use of reduction methods.

II. A fluid model of TCP behavior

The control design is based on the use of a fluid model of TCP dynamical behaviour, which was derived in [3] 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.

The model can be linearized obtaining the following set of linear time-delay ODEs [1]:

$$\begin{aligned}\delta\dot{W}(t) &= -\frac{N}{R_0^2C}(\delta W(t)+\delta W(t-R_0)) \\ &\quad -\frac{1}{R_0^2C}(\delta q(t)-\delta q(t-R_0)) \\ &\quad -\frac{R_0C^2}{2N^2}\delta p(t-R_0), \qquad (1)\\ \delta\dot{q}(t) &= \frac{N}{R_0}\delta W(t)-\frac{1}{R_0}\delta q(t),\end{aligned}$$

where $\delta W \doteq W - W_0$, $\delta q \doteq q - q_0$ and $\delta p \doteq p - p_0$, W is the average TCP window size (packets), q the average queue length (packets), T_p the propagation delay (s), R the transmission round-trip time ($R = \frac{q}{C} + T_p$), 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 non negative.

In what follows, for the sake of clarity, we will consider the same parameter values considered in [1], i.e. $C = 3750$ packets, $R_0 = 0.246$ s, $N = 60$ sessions, $q_{max} = 600$ packets corresponding to the steady-state operating regime $W_0 = 15$ packets, $q_0 = 200$ packets, $p_0 = 0.008$.

Sabato Manfredi, Mario di Bernardo and Franco Garofalo are with the Faculty of Engineering, University of Naples Federico II, Via Claudio 21, Napoli 80125, Italy.

*The authors are listed in alphabetic order.

**Corresponding author. Email: sabato.manfredi@unina.it

We observe that as shown in [1], the delay R_0 in the state term $\delta W(t-R_0)$ in (1) can be neglected when $W_0 \gg 1$.

Despite its limitations, the linear model has been successfully used to design effective AQM control schemes [1], [5], [7], [8], [9], [15], [16].

III. A STATE FEEDBACK APPROACH

In what follows, we recall the main aspects of the design of a state feedback control scheme for active queue management (AQM) which is robust to unwanted variations of parameter uncertainties as round trip time, load and link capacity (see [6] for further details). In so doing we will proceed in two stages. Firstly, a robust observer will be designed to estimate the transmission window online, avoiding the requirement for full state availability. Secondly, an appropriate robust controller for time-delay systems is synthesized to cope with round-trip time, load and link capacity variations.

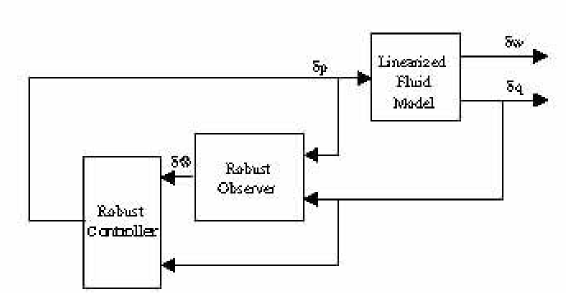


Fig. 1. Block Diagram of the proposed Robust AQM control scheme.

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 approaches recently presented in [10] and [19], [22]. A more detailed theoretical analysis of the schemes can be found in [8], [9].

We wish to emphasize that by using a robust observer, we were able to synthesize a full state feedback controller which, because of its nature, can guarantee better performance than other control scheme. In our case, the control action is based on the use of both states, the queue length q and the window size W. To solve this problem we propose to equip the control law with an appropriate robust observer for time-delay systems. It was shown that this is indeed possible and that a robust observer can be designed adapting the results presented in [10] 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. (See [8], [9] for further details.)

A. Two alternative approaches

In what follows, we will briefly present two alternative robust AQM controllers that coupled with the observer presented above can be used to implement the state feedback AQM control scheme shown in fig. 1. The first approach (see [8] for further details) is based on the use of a reduction method for time delay systems, leading to a control law with memory. The second (detailed in [8]) uses instead an H$^\infty$ theoretical synthesis approach resulting in a memoryless control law which is found to be more effective for practical applications through numerical and experimental tests. 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.

1) Robust reduction-based AQM Control (RRAQM): . The reduction transformation method presented in [18] can be briefly outlined as follows (see [18] for further details). Consider a time-delay system of the form

$$\begin{aligned} \dot{\mathbf{x}}(t) &= A\mathbf{x}(t) + B_d u(t-\tau), \\ y &= Cx(t), \end{aligned} \tag{2}$$

with state vector $x(t) \in R^n$, output $y(t) \in R^p$, input $u(t) \in R^r$, known and fixed nominal delay τ, initial conditions $x(0) = \Psi(t), t \in [-\tau, 0]$ and $u(t) = \Phi(t)$ for t$\in [-\tau, 0]$. The idea is to compensate the effects of the delay and stabilize (2) by considering the linear transformation

$$z(t) \doteq x(t) + \int_{t-\tau}^{t} e^{A(t-\tau-\alpha)} B_d u(\alpha) d\alpha.$$

Under this transformation, it can be shown (see [18]) that system (2) can be recast in terms of the new state variables z as the delay-free set of ODEs: $\dot{\mathbf{z}}(t) = A\mathbf{z}(t) + Bu(t)$, where the matrix B is defined as $B = e^{-\tau A} B_d$. Under the assumption that (A, B) is stabilizable, system (2) can be stabilized using a classical state-feedback designed on the reduced model (III-A.1) given by

$$u(t) = Kz(t) = K\left(x(t) + \int_{t-\tau}^{t} e^{A(t-\tau-\alpha)} B_d u(\alpha) d\alpha.\right) \tag{3}$$

The matrix K can be chosen according to one of the many available methods for delay-free dynamical systems. The main disadvantage of the reduction approach presented sofar is that it requires exact knowledge of the system equations. This is often impossible in real application, particularly in the case of communication networks. So we can consider parametric uncertainties in model (2) and design K in (3) that can robustly stabilize the system following the strategy presented in [19]. This approach was used to synthesise a novel robust AQM control approach based on the use of reduction methods.

However, the practical implementation of the control strategy can be cumbersome as the computation of the integral in the control law involves the storage of many additional variables depending on the choice of the sample time. Thus, in what follows we summarize an alternative memoryless H$^\infty$ AQM control approach that is shown to be more effective in practical applications (see [8], [9] for further details).

2) H^∞ state feedback control (RHC): The design of a robust H^∞ state feedback controller for continuous time systems with time-varying delays was recently discussed in [22]. 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.

As discussed in [22], it is possible to show that, for a given positive constant γ, the controller $u(t) = Kx(t)$ with K obtained by solving an appropriate LMI problem, renders an uncertain time-delay system quadratically stable with an H^∞ norm bound.

We consider for the parameter uncertainties in the model (1) 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 will be shown in Sec. IV, the controller validation in network-simulator, shows that the controller presented here performs well when applied to control a realistic TCP connection.

IV. Controller Validation on multibottleneck scenarious through NS-2

Now, we shall seek to validate the effectiveness of the H^∞ (shortly labelled as RHC) and Robust Reduction Method (shortly labelled as RRAQM) described above and compare their performance in classical multibottleneck scenarios [24], [25]. To this aim, we used NS-2, a network simulator widely used in the control and communication communities [17]. Simulations, refer to the general multibottleneck topology router using 5 level bottleneck topology (k=5) as depicted in Fig. 2.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..5) have a capacity of 100BaseT rate (100Mb/s) and a propagation delay of [40-60]ms. There are $N_{1,k+1}$ flows traversing all links. The nominal conditions include all N flows set to 30. We note that differently to previous multibottleneck test topologies we have introduced also the presence of cross-traffic flows $N_{k+1,1}$ (inverse to $N_{1,k+1}$). Indeed this traffic affects heavily the acknowledgment traffic delaying and/or eliminating it from the network. This can be seen as uncertainty on the round trip time. The average packet length is set to 1 Kbyte differently from the nominal value of 500 bytes used for control design. The choice of a different packet size is made here to further test AQM schemes under different network parameters. In real networks, the packet size is usually chosen depending on the particular application being considered and typically it is higher of 500 bytes. Indeed in the experiment the average packet size is around 1500 bytes. The parameters of the RHC and RRAQM controllers are those recommenced in [9]. The sampling frequency schemes is $f_s = 160$Hz. We report below a variety of numerical simulations and experiments. Namely, we investigate the (i) nominal case with different packet size; (ii) the robustness of AQM controllers to network dynamic parameter uncertainties (load and round trip time); (iii) the dynamic behaviour in the presence of UDP flows and cross traffic. In particular, we evaluate the average and standard deviation of the routers queue length in order to verify the AQM robust control effect on queue stabilization and therefore on queueing and jitter delays. In particular high queue standard deviation implies variable round trip time for the sources and also low queue utilization if the queue goes frequently to zero. In order to better evaluate the differences in the controllers performance standard deviation we have chosen a relatively large queue (buffer size of 600packets).

A. Nominal case with different packet size and cross traffic

We validate AQM controllers upon the topology described above when the packet size is fixed to the value of 1000 bytes (differently to the nominal 500 bytes) as further validation of AQM controllers upon different packet size. The different packet size for the model point of view correspond to a different operating point of the network. Then we have considereds the presence of inverse cross traffic $N_{k+1,1}$, $k = 5$ that correspond to dynamic queue delay (and so round trip time) variations. We note in Fig. 3 that both controllers presents good behavior under different static operating point.

B. Random TCP connections and round trip time variations

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

We can observe in Fig. 4 that also in this case the robust controllers deal with dynamic uncertainties in the load and round trip time 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 RRAQM.

C. Dynamic behaviour in presence of UDP flows and cross traffic

An important aspect is the possible presence on the network of unresponsive sources, whose traffic clearly affects the overall network dynamics. The UDP dynamic not only causes load and round trip time variations, but also an equivalent capacity reduction perceived by tcp flows. In particular, we study the effects of adding UDP flows (500Kbit/s - *CBR - Constant Bit Rate*) to nominal traffic that are switched on at $t = 50$ s and turned off when $t = 100$ s. We have also considered the presence of inverse cross traffic $N_{6,1}$. We note in Fig. 5 the faster response time of the RHC and better UDP traffic rejection (by reducing its propagation through bottleneck levels) with respect to RRAQM scheme (Fig. 6).

V. Conclusions

We have discussed the effectiveness of improved AQM control schemes to address the issue of variations of the network parameters unavoidable in practical applications.

In particular RHC strategy was shown to be particularly effective on realistic multibottleneck network scenarious and both in presence of cross traffic and UDP flows. Note that, for the sake of brevity we have omitted standard AQMs controller (i.e. PI, RED, REM, AVQ, VRC). Our experiments show that those schemes present an overall (static and dynamic behaviour) lower robustness performance in single-multi bottleneck uncertainty scenarios with respect to the robust AQMs schemes (refer to [8], [9] for further details). Here the main idea is to compare the performance of the two AQM robust schemes presented in [8], [9] in the multibottleneck scenarios. We note that the simulations presented above show faster responsiveness of RHC with respect to RRAQM. This is due to the memoryless nature of RHC. Besides, the practical implementation of the RRAQM control strategy involves the computation of the integral in the control law and the storing additional variables. Ongoing research include the formal extension to multibottleneck scenarios of robust controller.

REFERENCES

[1] C. V. Hollot, V. Misra, D. Towsley, W. Gong, "Analysis and Design of Controllers for AQM Routers Supporting TCP Flows", *IEEE ACM Trans on Automatic Control*, Vol 47, no. 6, pp. 945-959, 2002.

[2] Y. Chait, C. V. Hollot, V. Misra, S. Oldak, D. Towsley, W. Gong, "Fixed and Adaptive Model-Based Controllers for Active Queue Management", *Proc. American Control Conference*, pp 2981-2986, 2001.

[3] V. Misra, W. B. Gong, and D. Towsley, "Fluid-based analysis of a network of AQM routers supporting TCP flows with an application to RED", *ACM SIGCOMM*, 2000.

[4] S.H. Low, F. Paganini, J.C. Doyle, "Internet Congestion Control", *IEEE Control Systems Magazine*, pp. 28-43, 2002.

[5] E.C. Park, H. Lim, K.J. Park, and C.H. Choi, "Analysis and Design of the Virtual Rate Control alghorithm for stabilization Queues on TCP networks", *Comput. Networks*, Vol.44, N.1, pp.17–41 2003

[6] S. Manfredi, M. di Bernardo, F. Garofalo, "A Robust Approach to Active Queue Management Control in Networks", *Proceedings of the 2004 International Symposium on Circuits and Systems*, Vol 5, no 5, pp:485-488, 2004

[7] P.F. Quet and H. Ozbay, "On the Design of AQM Supporting TCP Flows Using Robust Control Theory", *IEEE Transactions on Automatic Control*, Vol 49, no 6, pp:1031-1036, 2002.

[8] S. Manfredi, M. di Bernardo, F. Garofalo, "Synthesis of robust active queue management controllers", *Proceedings of* 16^{th} *International Symposium on Mathematical Theory of Networks and Systems*, Belgio, 2004

[9] S. Manfredi, M. di Bernardo, F. Garofalo "Robust Output feedback Active Queue Management Control in TCP Networks", *Conference on Decision and Control*, Bahamas, Vol 1, pp:1004-1009, 2004.

[10] A. Fattouh, O. Sename, J. M. Dion, "A LMI approach to robust observer design for linear time-delay systems", *Proc. of the* 39^{th} *IEEE Conference on Decision Control*, Sydney, Australia, pp. 1495-1500, 2000.

[11] L. Massoulie, "Stability of distribuited congestion control with heterogeneous feedback delays", *Microsoft Research Technical Report*, 2000.

[12] H. Ozbay, S. Kalyanaraman and A. Iftar "On rate based congestion control in high speed networks: design of an H^{∞} based flow controllerfor single bottleneck", *American Control Conference*, vol.4 pp. 2376-2380, 1998.

[13] P.H. Quet, B. Ataslar, A. Iftar, H. Ozbay, T. Kang and S. Kalyanaraman "Rate based floe controllers for communication networks in the presence of uncertain time varying multiple time delays", *Automatica*, vol.38, pp. 917-928, 2002.

[14] P.H. Quet, P. Yan, and H. Ozbay "H^{∞} and LMMSE based capacity predictors for flow control in communication networks", *submetted for pubblication to Automatica*, February 2002.

[15] R. Fengyu, L. Chuang, Y. Xunche, S. Xiuming, W. Fubao "A robust Active Queue Management Algorithm based on Sliding Mode Variable Structure Control", *Infocom'02*, New York, pp. 64-79, 2002.

[16] Z. Heying, L. Baohong, D. Wenhua "Design of a Robust Active Queue Management Algorithm based on Feedback Compensation", *Sigcomm'03*, 2003.

[17] J. Fall, K. Varadhan, "The ns manual", 2001.

[18] Know, W.H. and A.E. Pearson, "Feedback stabilization of linear systems with delayed control", *IEEE Trans. Automatic Control*, Vol. 25, no. 2, pp. 266-269, 1980.

[19] Y. S. Moon, P. Park, W. H. Kwon, "Robust stabilization of uncertain input-delayed systems using reduction method", *Automatica*, vol.37, pp. 307-312, 2001

[20] K.Ramakrishnam and S.Floyd, "A proposal to add Explicit Congestion Notification (ECN)to ip", *RFC 2481*, 1999.

[21] S. Athuraliya, S.H. Low, V.H. Li, Q. Yin, "REM: Active queue managment", *IEEE Network*, Vol 15, no 3 pp. 48-53 2001.

[22] J.H. Kim, H.B. Park, "H^{∞} state feedback control for generalized continuous/discrete time-delay system", *Automatica* 35, pp. 1443-1451, 1999.

[23] S. Floyd and V. Jacobson, "Random Early Detection gateways for congestion avoidance", *IEEE/ACM Transactions on Networking*, Vol.1, no.4, pp. 397-413 1993.

[24] P.F. Quet and H. Ozbay, "A Variable Structure Control Approach to Active Queue Management for TCP with ECN",*IEEE Symposium on Computers and Communications*, 2003.

[25] A.Kantawala and J.Turner, "Queue management for short-lived TCP flows in backbone routers", *IEEE GLOBECOM '02*, Volume 3, pp. 17-21, 2002.

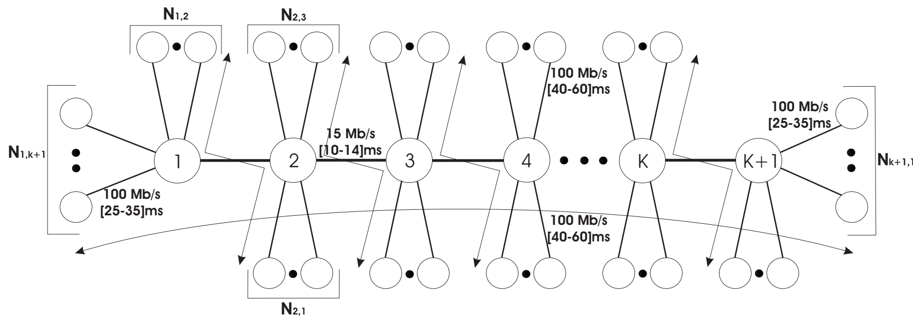
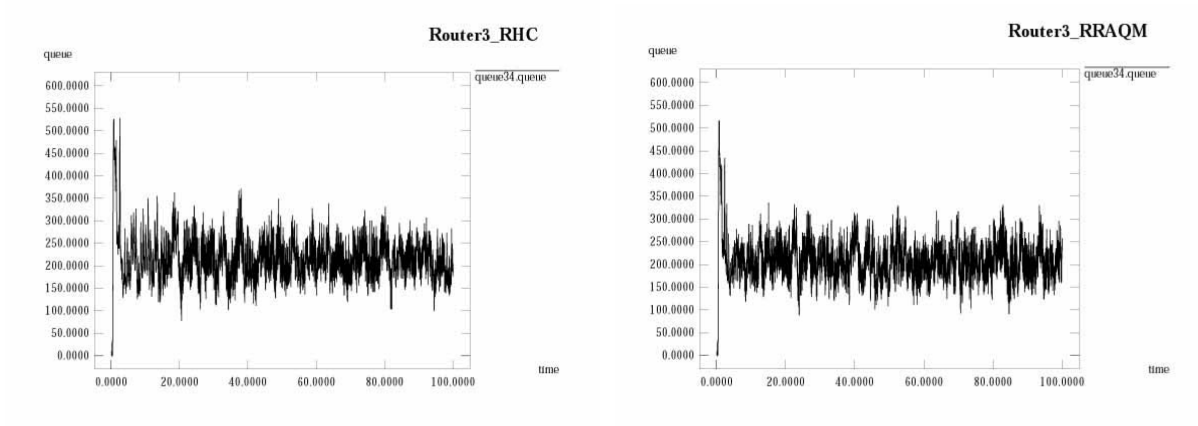


Fig. 2. Multibottleneck topology

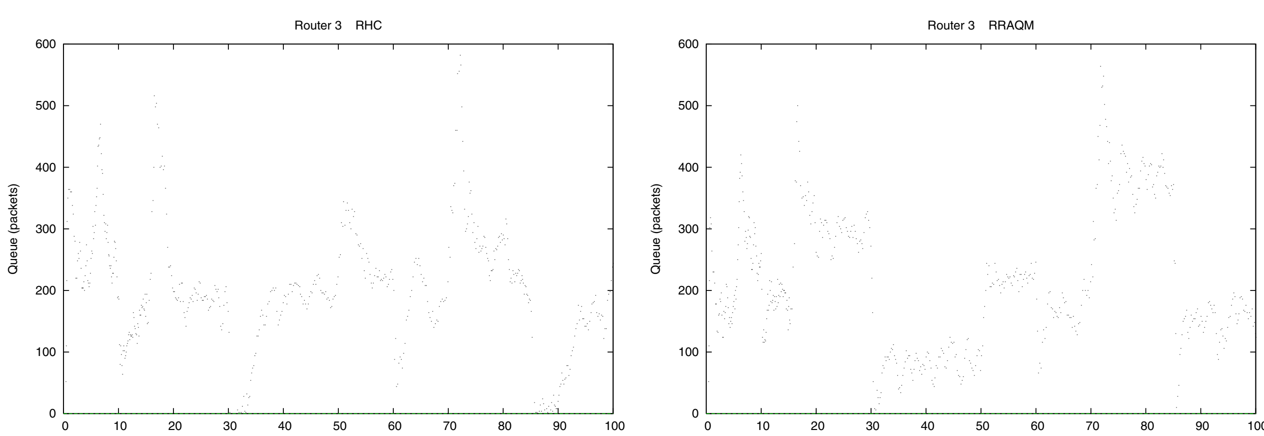


(a) **(b)**

Fig. 3. Time evolution of queue length at the router 3 in presence of different packet size and cross traffic: **(a)** RHC; **(b)** RRAQM

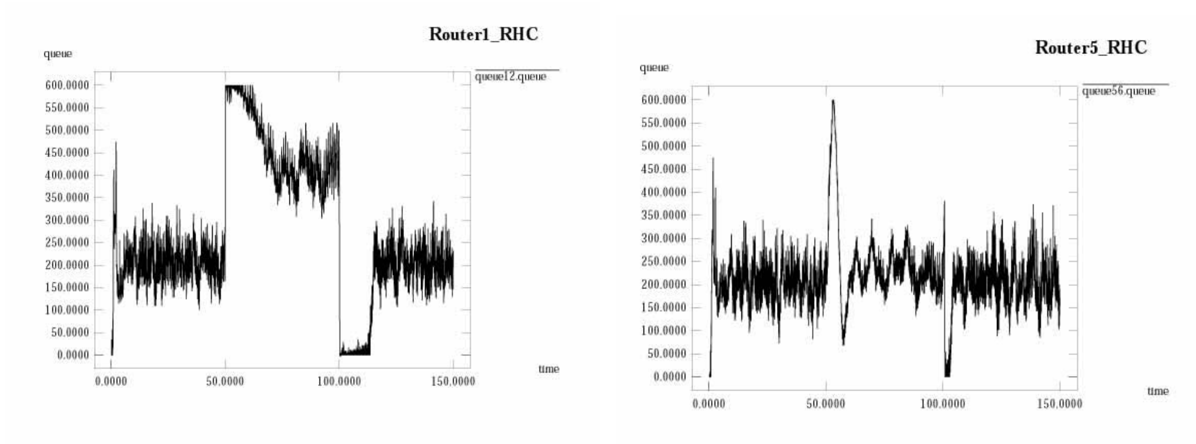
Time Interval[sec]	$R = \frac{q_0}{C} + T_p$ [sec]	Time Interval [sec]	N
0-10	[0.306-0.386]	0-5	60
10-15	[0.266-0.346]	5-15	90
15-20	[0.386-0.466]	15-30	140
20-30	[0.266-0.346]	30-50	50
30-40	[0.173-0.306]	50-60	120
40-60	[0.266-0.346]	60-70	90
60-80	[0.413-0.493]	70-85	180
80-100	[0.226-0.306]	85-100	80

TABLE I
DYNAMIC LOAD N AND ROUND TRIP TIME R VARIATIONS



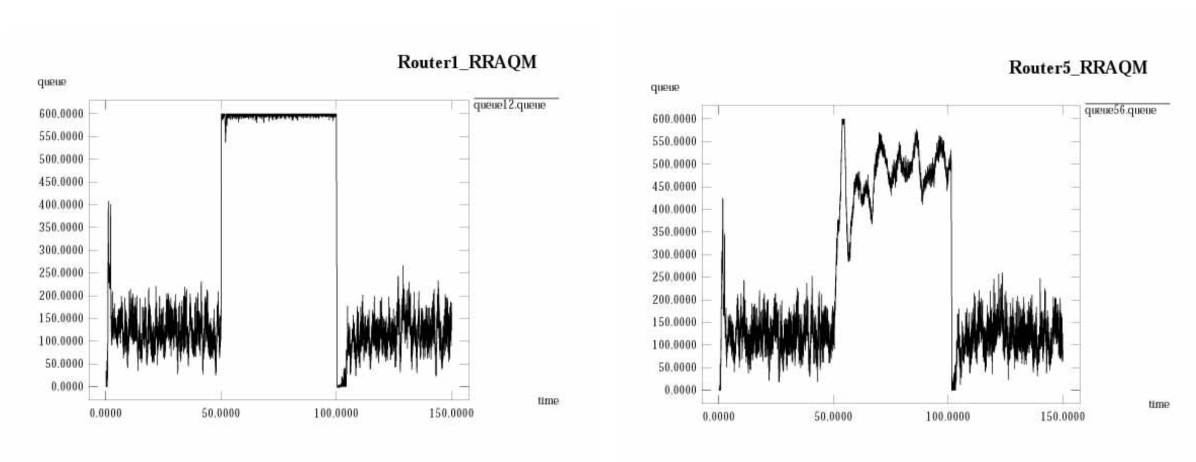
(a) **(b)**

Fig. 4. Time evolution of queue length at the router 3 in presence of load and round trip time variation in Table 1: **(a)** RHC; **(b)** RRAQM



(a) **(b)**

Fig. 5. Performance of RHC controller in presence of UDP and cross traffic flows: **(a)** time evolution of the queue length at the Router 1; **(b)** time evolution of the queue length at the Router 5;



(a) **(b)**

Fig. 6. Performance of RRAQM controller in presence of UDP and cross traffic flows: **(a)** time evolution of the queue length at the Router 1; **(b)** time evolution of the queue length at the Router 5;