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Cooperative Rate Control in ATM Networks

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Abstract— **This paper introduces the concept of a bottleneck-switches cooperation in the explicit rate-control framework of Asynchronous Transfer Mode (ATM) networks. The proposed controller regulates the rates of available bit rate (ABR) traffic class and requires only local information exchange between bottleneck nodes. A sufficient condition for network closed loop stability is given and it is used for switch-controller parameters design. A realistic numerical validation is carried out by a discrete packet simulator.**

keyword: ATM networks, rate control, cooperative control.

I. Introduction

Todays Internet only provides Best Effort Service by processing traffic as quickly as possible without guarantee any Quality of Service (QoS)[1]. With the rapid increase of demands for Internet service quality it is becoming apparent the business opportunity for the web-companies in developing several service classes will likely be demanded. The introduction of new types of services in the fixed and mobile communication networks underlines as the problem of network congestion control remains a critical issue. In this scenario Asynchronous Transfer Mode (ATM) is a one of the key technology for integrating broadband integrated services (B-ISDN) in heterogeneous networks where data, video and voice sources transmit information. To support multimedia traffic, the ATM Forum [2] has defined different service classes of which Available Bit Rate (ABR) is one that responds to network congestion by means of a feedback control mechanism. In particular a feedback signal may be in the form of an Explicit Rate (ER) provided on an end to end basis via Resource Management (RM) cells. Usually ABR traffic is not sensitive to service rates nor delays but is sensitive to packet loss so that the throughput of a connection can be decreased as much as necessary, in order to alleviate congestion. In ATM networks, the ABR class is served only if there is some bandwidth left by the constant bit-rate (CBR) class or/and the variable bit rate (VBR) class which get the higher scheduling priority. So, at a given switch buffer, when both ABR traffic and CBR/VBR traffic are backlogged, the packets from the higher quality of service traffic are processed first, and the best effort traffic is served only if there is some bandwidth left by the CBR/VBR traffic. So if the rate of each ABR source is not controlled, congestion may be caused. Associated with each switch buffer there is a rate controller that computes the explicit rate (ER) for each user in order to efficiently allocate the unused bandwidth of link to the ABR traffic and avoid buffer overflow.

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Many papers in the literature consider the problem of designing the ATM controller at bottleneck link dealing with ABR traffic flows. In [3] a control scheme based on a Smith's predictor is presented that, although it obtains good set point regulation, it can be sensitive to the delay uncertainties. In [4], [5], robust controllers are designed for guaranteeing robustness against multiple time-delays, set point queue length regulation at the bottleneck link while it is satisfied a weighted fairness condition. In [6], it is shown that the stability of the congestion control system with a single source is equivalent to the stability of the one with multiple sources for linear controller, concluding that if the system is stable for a single source it will be stable for an arbitrary large number of sources. In [7] the authors design a PD controller, where the control parameters can be designed to ensure the closed loop stability over a wide range of propagation delays. In [8] is discussed how to use the RouthHurwitz stability criterion to design and analyze the stability of a flow control algorithm with feedback delay for ABR traffic, while in [9] a novel integral sliding mode control strategy is designed for rate control problem in ATM networks. In [10] the authors introduced an algorithm enhancements for convergence rate improvements, queue management, and a coefficient bias reduction without compromising the computational complexity. All the aforementioned approaches concern the design of the rate regulator that uses local information at the switch for control purpose (i.e. queue length, virtual rate) and most of their theoretical results refer to the case of single bottleneck scenarios. In this work, we would like to introduce a concept of a cooperative-based rate control in the explicit-rate control framework of ATM-networks. The basic idea of the proposed strategy is to enhance rate control protocol functionality through bottleneck nodes coordination in order to alleviate and to mitigate congestion effects on the network performance. Moreover, we consider a multibottleneck scenario in the presence of time delayed heterogeneous sources. In the recent years distributed coordination of multi-agent systems have received significant attention (i.e see [11] and reference therein). One common feature of this research is to allow every network agent automatically address a common objective using only local information received from its neighboring agents. To our knowledge, despite of the successful application of multi-agent approach in several applications (i.e. formation flight, robot swarm), the development of network rate control based on cooperative theoretic concepts is quite unexplored. In particular the paper focus on the introduction of Cooperative Rate Control (in the follows briefly CRC) scheme in order to i) stabilize the ATM network; ii) balance the network queues length at a desiderate

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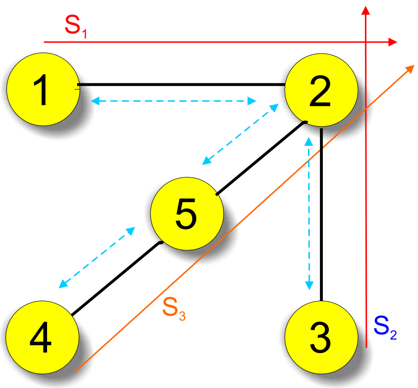

Fig. 1. ATM Network graph

set point value, reducing packet loss and improving link utilization; iii) enhance the controller robustness to load and round trip time variations; iv) guarantee max-min fair bandwidth allocation to the sources. Moreover, the presence of multi-bottleneck and heterogeneous sources time delay is taken into account in the problem formulation. The control requires only local information exchange between bottleneck nodes. Finally, we use ATM packet simulator to demonstrate that the proposed control can be implemented and that it achieves the network desired behavior in a more realistic scenarios.

The rest of the paper is outlined as follows. In Sec. II, an ATM multibottleneck model used in this paper is described. In Sec. III, a cooperative rate control and closed loop stability condition are presented. The effectiveness of the control law is validated and tested through packet numerical simulations in Sec. IV. Finally, conclusions are outlined in Sec. V.

A. Notation

Given a vector x$\in$ $\mathbf{C}^n$, x$_i$ denotes its i-th component, while $X = diaggen\{$x$\}$ is a diagonal matrix in $\mathbf{C}^{n\times n}$ generated by the vector x and having x as diagonal. Given a matrix A, $\sigma(A)$ denotes the spectrum of A while $f(A)$ is the field of values of A. For a set V$\subset$ $\mathbf{C}$, Co(V) denotes the convex hull of V, while $|V|$ denotes the cardinality of V. For a square matrix B with real eigenvalues, $\lambda(B)$ denotes its spectrum, λ_m (λ_M) denotes the algebraically smallest (largest) eigenvalue. Finally, s denotes a Laplace complex variable.

Let $G(N, E, A)$ be a graph with the set of links N, set of edges $E \subseteq N \times N$, and an adjacency matrix $A = \{a_{ij}\}$ with nonnegative adjacency elements. The set of neighbors of i-th link is defined by $N_i = \{k\epsilon N : a_{ik} = 1\}$. Considering an undirect graph, the degree value d^i of link i is the number of the neighbors of link i-th (e.g. $|N_i|$). The Laplacian matrix $L = [l_{ij}]$ is defined by:

$$l_{ij} = \begin{cases} \sum_{j=1, j\neq i}^{N} a_{ij}, & i = j; \\ -a_{ij}, & i \neq j. \end{cases}$$

By the Laplacian definition results: $L = D - A$ with D is the $|N| \times |N|$ diagonal matrix having in position i-th the degree value d^i of the link i-th. We define the *extended Laplacian* as $\tilde{L} = L + I$, with I being the identity matrix of opportune dimensions.

II. An ATM Network model

In the recent years various dynamic models have been used by a number of researchers to model a wide range of queueing and contention systems. Several variants of the fluid model have been extensively used for network performance evaluation and control (i.e. [5], [12]). Here, the main objective is to consider a low order complexity model of multi-bottleneck capturing the essential dynamics of network behavior which is suitable for a decentralized cooperative control design. Moreover, we would like to consider in the model the presence of time-delays in the sources data-flow. A time-delay is due the time elapsed between a rate command signal by a switch controller and the actual time this rate is set. This delay from the control input to the regulated output is the sum of two delays (backward delay τ_b from controller to source and forward delay τ_f from source to controller) named the *round-trip time delay* RTT. Considered a network graph consisting by a set of congested links $N = \{1, 2, .., n\}$ and $M = \{1, 2, .., m\}$ accessing sources by a specific source-destination path (i.e in Fig. 1 $n = 4$ and $m = 3$), the source-link interconnections can be described by the routing-matrix:

$$R_{ij}(s) = \begin{cases} e^{-s\tau_{i,j}}, & \text{if source j traverses link i;} \\ 0, & \text{otherwise.} \end{cases}$$

with $\tau_{i,j}$ denoting the delay of the source j with respect to (w.r.t) link i. For sake of notation we denote with $R^f_{ij}(s)$ the forward routing matrix of elements $e^{-s\tau_{f_{i,j}}}$ with $\tau_{f_{i,j}}$ is the forward time delay from source j to link i, and let $R^b_{ij}(s)$ the backward routing matrix of elements $e^{-s\tau_{b_{i,j}}}$ with $\tau_{b_{i,j}}$ is the backward time delay from link i to source j. In this way, the source j-th has w.r.t link i-th the round trip time: $RTT_{i,j} = \tau_{f_{i,j}} + \tau_{b_{i,j}}$. Starting from the fluid queue model of a single bottleneck and multiple time delayed sources widely used in the literature (i.e. [3], [4], [5], [6]), and denoted with n_i the number of source connections accessing to the i-th bottleneck link, $q_i(t)$ the queue length at the bottleneck link i-th and $r_{_{i,j}}(t)$ being the data flow rate of the j-th source, the ATM network dynamic model is described by:

$$\dot{q}_i(t) = \sum_{j\epsilon\bar{S}_i} r_{i,j}(t - \tau_{f_{i,j}}) - c_i(t)$$

for $i\epsilon N$ and $j\epsilon\bar{S}_i = \{s\epsilon M : s \text{ across the link } i - th\}$ and $c_i(t)$ being the rate at which data is sent out from the link. For sake of clarity we introduce the set of *virtually bottleneck neighbors* of i-th link defined as $N_i = \{k \in N : \bar{S}_i \bigcap \bar{S}_k \neq \emptyset, a_{ik} = 1\}$. In other words, *virtually bottleneck neighbors* are bottlenecks sharing source paths. For instance referring to Fig. 1, the output link of node 2 and the links $1 \mapsto 2$, $3 \mapsto 2$ share the paths of the sources S_1, S_2 and S_3 and so they are *virtually bottleneck neighbors*. The overall graph composed of bottleneck nodes and their virtual neighbors is a *virtual graph*. According to the rate control strategies presented in the literature (see i.e. [3]-[10] and references therein), we consider that source rates $r_{i,j}(t)$ will be assigned to the sources j-th by a feedback controller $u_{i,j}$ located at the bottleneck i-th resulting in the following closed loop model:

$$\dot{q}_i(t) = \sum_{j \epsilon \bar{S}_i} u_{i,j}(t - RTT_{i,j}) - c_i(t) \quad (1)$$

with $RTT_{i,j}$ is the round trip time of the source j-th w.r.t link i-th. We note that the source rate commands $u_{i,j}$ should satisfy the constrain on the aggregate available rate u_i computed by the controller. So if $u_{i,j} = k_{i,j} u_i$, $k_{i,j}$ are non negative controller parameters to be fixed so that $\sum_{j \epsilon \bar{S}_i} k_{i,j} \leq 1$. Let us assume ([2]) that the source j-th sends packets according to the minimum rate value u_{mj} among the rate values assigned by the links along the path of its flow (i.e. $u_{mj} = \min_i u_{i,j}$ with $i \epsilon B_j = \{l \epsilon N : l$ is a bottleneck for the source $j\}$). Because the minimum operation is taken over a finite number of links and each flow j-th has at least one bottleneck on its path, there should exist u_{mj}, $\forall j \in M$.

We do the following assumptions: $A.1$) we assume that the sources are persistent until the closed-loop system reaches steady state meaning that the source always has enough data to transmit at the allocated rate; $A.2$) we assume all links to be bottleneck so we can assume $c_i(t) = c_i$ with c_i to be the i-th link capacity. In the next section we will introduce a cooperation based rate control at the bottleneck link that adjusts sources rate according to both its own congestion level (i.e. queue length) and that of its *virtually bottleneck neighbors*.

III. Cooperative Rate Control

In what follows we will present a coperative rate control and a we will give a sufficient condition for network closed loop stability that can be used for controller parameters design.

Theorem 1: Consider a n-links m-sources communication network described by (1). Chosen the cooperative control action $u_{i,j}(t) = k_{i,j} \sum_{k \epsilon N_i \bigcup \{q_0\}} (q_k(t) - q_i(t)) + k_{f_{i,j}} \hat{c}_i(t)$, then the following hold:

a) the network is globally asymptotically stable if

$$k_{i,j} < \frac{\pi}{2|\bar{S}_i| RTT_{Mi} \lambda_M}, \quad (2)$$

$\forall i \epsilon N$, $\forall j \epsilon \bar{S}_i$, with $RTT_{Mi} = \max\{RTT_{i,j}, j \epsilon \bar{S}_i\}$, λ_M maximum eigenvalue of $\tilde{L}$, $k_{f_{i,j}} \hat{c}_i(t)$ is a feedforward action for link capacity allocation with gain $k_{f_{i,j}}$ and link capacity estimation $\hat{c}_i(t)$.

b) the network queues asymptotically converge to the same set point value q_0 with resulting queue balancing state.

We remark that the control law $u_{i,j}(t)$ is composed by the feedback cooperative term $k_{i,j} \sum_{k \epsilon N_i \bigcup \{q_0\}} (q_k(t) - q_i(t))$ (including the pinning term in q_0) and by the feedforward action term $c_{fi,j} = k_{f_{i,j}} \hat{c}_i(t)$. So we need to design feedback gains $k_{i,j}$ and feedforward gains $k_{f_{i,j}}$.

Note that from A.2 we have $\hat{c}_i(t) = c_i$ and results $c_{fi,j} = k_{f_{i,j}} \hat{c}_i(t) = k_{f_{i,j}} c_i$. We design $c_{fi,j}$ in order to allocate the i-th link capacity c_i, fulfilling the constraint that the total capacity made available to sources is less or equal than c_i. In particular, choosing $k_{fi,j}$ according to

$$\frac{w_j}{\sum_{k \epsilon \bar{S}_i} w_k} \quad (3)$$

with w_j being the priority-weight associated to the source j-th, the amount of capacity allocated to the j-th source then results: $c_{fi,j} = \frac{w_j}{\sum_{k \epsilon \bar{S}_i} w_k} c_i$. In so doing, the allocation of the available capacity among sources guarantees not only that the allocated capacity is within bounds but also that the allocation is proportionally fair. With proportional fairness, sources with greater weights w_j are allocated a larger amount of capacity, causing an heavy reduction in the allocation for other sources. We can interpret w_j as pre-assigned level of Quality of Service to the source j-th. Thus (3) can be used for feedforward gains $k_{f_{i,j}}$ design purpose in order to fair allocate the available capacity c_i on the base of source priorities. In particular, in the case of equal w_j for all j, the resulting capacity allocation is *max-min fair*. In what follows we will give a proof of Theorem 1 that can be used for feedback gains design.

Without loss of generality, we assume $k_{i,j} = k_i \ \forall j \epsilon \bar{S}_i$. In so doing all sources sharing a common link receive the same rate command signal $u_{i,j} = k_i u_i$, $\forall j \epsilon \bar{S}_i$.

Proof: a)
The cooperative feedback term at link i-th regulates the sources rate according to both its level of congestion q_i and the level of congestion q_k, $k \epsilon N_i$ of its neighbors. Substituting $u_{i,j}$ in the closed loop equation (1) and being $\sum_{j \epsilon \bar{S}_i} k_{f_{i,j}} \hat{c}_i(t) = \sum_{j \epsilon \bar{S}_i} k_{f_{i,j}} c_i = c_i$ by chosen $k_{f_{i,j}}$ according to (3), then results:

$$\dot{q}_i(t) = \sum_{j \epsilon \bar{S}_i} k_{i,j} \sum_{k \epsilon N_i \bigcup \{q_0\}} (q_k(t - RTT_{i,j}) - q_i(t - RTT_{i,j})).$$

Considering $k_{i,j} = k_i$ and separating the set point term in q_0, we obtain:

$$\dot{q}_i(t) = \sum_{j \epsilon \bar{S}_i} k_i (\sum_{k \epsilon N_i} (q_k(t - RTT_{i,j}) - q_i(t - RTT_{i,j})) + \\ + q_0 - q_i(t - RTT_{i,j})); \quad (4)$$

$$\dot{q}_i(t) = k_i \sum_{j \epsilon \bar{S}_i} (\sum_{k \epsilon N_i} (q_k(t - RTT_{i,j}) - q_i(t - RTT_{i,j})) + \\ - q_i(t - RTT_{i,j})) + k_i |\bar{S}_i| q_0.$$

Notice that $\sum_{k \epsilon N_i} (q_k(t) - q_i(t)) - q_i(t)$ represents the $i-th$ element of product $-\tilde{L} q(t)$ with $q(t) = [q_1, .., q_n]^T$ being the vector of network queue lengths at the time t. Defined $\tilde{R}(s)$ the delay diagonal matrix with $\sum_{j \epsilon \bar{S}_i} e^{-sRTT_{i,j}}$ on the i-th diagonal position, $K = diaggen\{k\}$ the controller feedback gain matrix, $P(s) = diaggen\{\frac{1}{s}\}$ the queue process then the controlled network reduces to the feedback control system with q_0 as reference queue length and having the following return ratio transfer function:

$$H(s) = K \tilde{R}(s) P(s) \tilde{L}.$$

Beside results:
$\sigma(H(s)) \subset f(K\tilde{R}P\tilde{L}) \subset f(K\tilde{R}P)f(\tilde{L}) = Co\{k_i\tilde{r}_ip_i\}Co\{\lambda(\tilde{L})\} \subseteq Co\{k_i\sum_{j\epsilon\bar{S}_i}\frac{e^{-sRTT_{i,j}}}{s}\}[\lambda_m,\lambda_M]$.
Indeed being the matrices *normal* [13] the first and the second above inclusions follow from the spectral containment and field values properties, the next equality follows from the normality property [13]. We note that the real part of the set $Co\{k_i\sum_{j\epsilon\bar{S}_i}\frac{e^{-sRTT_{i,j}}}{s}\}$ is lower limited by the point $-k_iRTT_{Mi}|\bar{S}_i|\frac{2}{\pi}$ when we set $RTT_{i,j} = RTT_{M_i}, \forall j\epsilon\bar{S}_i$ and $sRTT_{M_i} = jw\frac{\pi}{2}$.
So chosen $k_{f_{i,j}}$ according to (3), if (2) holds then $H(jw)$ do not intersect $(-\infty,-1]$ for all w and for the Generalized Nyquist criterion [14] the closed loop system is global asymptotically stable. This completes the proof a). ■

Proof: b)
One expectant goal of the proposed cooperative law is to bring the network to the balanced desired equilibrium so that $q_i = q_0$, for all $i \in N$, with q_0 being the target value for the all network queues. Indeed the ATM network under the proposed cooperative control law $u_{i,j}$ presents the equilibrium point $\bar{q}_i = q_0$, for all $i \in N$ as easily results from the closed loop equation (4). We show the convergence of the network to the above equilibrium point by computing the set point error $e(t)$ between the queue values and the step reference $\frac{q_0}{s}1_n$ with 1_n being the n dimension vector of all 1. Let $S_o(s)$ the sensitivity function of the closed loop system, from the final value theorem the steady-state value of the set-point error results:

$$\lim_{t\to\infty} e(t) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} sS_o(s)\frac{q_0}{s}1_n =$$
$$= \lim_{s\to 0} s(sI + K\tilde{R}(s)\tilde{L})^{-1}q_0 1_n = 0$$

being K a stabilizing controller for *proof a)*, $S_o(0) = 0$ and $K\tilde{R}(0)\tilde{L}$ an invertible matrix [1]. This completes the proof of Theorem 1. ■

Remark 1: Observing the condition (2), we note that the network stability depends: i) on the feedback gains $k_{i,j}$; ii) on the number of sources and round time delay; iii) on the virtual interconnection topology by the largest extended Laplacian eigenvalue λ_M. Being $RTT_M = \tau_{p_M} + B/c_i$ with τ_{p_M} is the maximum propagation delay and B is the buffer size of the i-*th* link, then (2) becomes $k_{i,j} < \frac{\pi}{2|\bar{S}_i|(\tau_{p_M}+B/c_i)\lambda_M}$. Therefore we can tune the feedback controller gains $k_{i,j}$ depending on the network parameters (i.e. link capacity c_i, buffer length B).

IV. Controller validation

Now, we shall seek to validate the effectiveness of the CRC controller derived above and compare its performance with respect to standard ATM congestion controller schemes in classical multibottleneck scenarios. To this aim we used the NISTHFC ATM network simulator [15] (in the follows shortly NIST), a packet network simulator developed to provide a means for researchers and network planners to analyze the behavior of ATM networks. The aim of the packet simulator validation is twofold. Firstly, to test the controller performance in a more realistic environment taking into account also the effects of discretization and nonlinear nature of network behavior. Secondly, to assess that the proposed protocol can be implemented by using the existing packet signaling of ATM protocol: it is used the available field of RM cell for sending control information between the neighbor links. Moreover, we compare the CRC performance with respect to standard ATM rate controller scheme ERICA (Explicit Rate Indication for Congestion Avoidance) algorithm [16] and EPRCA [17].

[1]Indeed it is strictly diagonally dominant matrix and hence for Geršgorin theorem is invertible

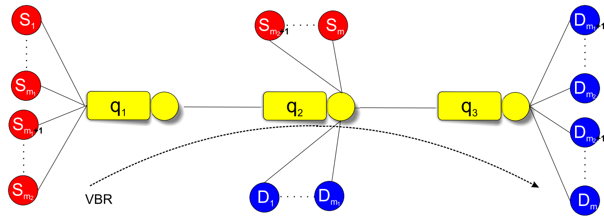

Fig. 2. NIST Experiment - Multibottleneck scenarios

Simulations refer to the general multibottleneck topology composed by 3 bottleneck level as depicted in Fig. 2 connected by links with capacities of 155Mb/s. The source-destination paths are detailed in Table I. Ordinary sources have minimum bit rate of 100Mb/s and maximum bit rate of 160Mb/s. Moreover, for heavy overloading the switches, we consider also the presence of VBR traffic as disturbance with average rate of 100Mbit/s, burst average length 2ms, burst period of 5ms and cells average generation 300. The target queue length q_0 corresponds to 180 cells (60% of the buffer switch length).

Source	Path	Destination
S_1 ... S_{m_1}	q_1 - q_2	D_1 ... D_{m_1}
S_{m_1+1} ... S_{m_2}	q_1 - q_2 - q_3	D_{m_1+1} ... D_{m_2}
S_{m_2+1} ... S_m	q_2 - q_3	D_{m_2+1} ... D_m

TABLE I
Source-Destination paths

The sampling period of the CRC control scheme is 2ms. For all other schemes the controller parameters, the sampling frequency, such as the rest of unspecified parameters, are fixed to values recommended in the original papers and in NIST simulator. Namely, we investigate (i) nominal case (ii) the robustness of CRC to network parameter uncertainties in terms of load and round trip time variations. We evaluate the performance calculating link utilization, packet loss and JAN index. The latter index quantifies how much the allocation is unfair with respect to the max-min one [18]. So, in what follows we'll consider for sake of example the case of max-min resource allocation (i.e. sources have the same priority w_j and $k_{f_{i,j}} = 1/\bar{S}_i\ \forall j\epsilon\bar{S}_i$).

A. Nominal case

We consider the CRC algorithm under nominal condition and in the presence of VBR traffic. The CRC feedforward gains are tuned for max-min resource allocation purpose (e.g. sources have assigned the same priority w_j and $k_{f_{i,j}} = 1/\bar{S}_i \ \forall j \epsilon \bar{S}_i$), while the CRC feedback gains are designed according to (2). Table. II shows the steady state value of the switch queue length as $\%$ of the buffer size. Notice that the CRC guarantees queue balancing and set point regulation than the other controllers.

	Switch$_1$	**Switch$_2$**	**Switch$_3$**
CRC	59	60	60
ERICA	5	30	4
EPRCA	15	5	6

TABLE II

STEADY STATE VALUE OF THE SWITCH QUEUE LENGTH

B. Robustness to load and round trip time uncertainties

In the follows we evaluate the robustness and the fairness performance of the CRC controller in the presence of both static load and round trip time variations.

1) Robustness to load variations: we consider the multi-bottleneck topology introduced above and repeat the simulation for different load N varying from 5 to 80. For each value of the load, we compute the link utilization and the Jan index for each switch. As shown in Fig. 3, the EPRCA and ERICA control schemes present the worsening of performance when the load increases. Differently, CRC scheme presented in this paper achieves a good queue stabilization with packet loss reduction and max-min fair link utilization also in the presence of load network uncertainty. This is very important point since the CRC controller presents a good scalability feature avoiding the performance degradation (packet losses, fairness, link utilization) even for increasing source demands considerably exceeding the link capacity.

2) Robustness to variations of the round trip propagation delay: we now consider variations of the average round trip propagation delay between 0.1 and 0.8 s. In Fig. 4, the performance indexes are reported as a function of the round trip time variations. Also in this scenarios, the CRC scheme shows the best performance when compared than the other controllers. This is due to the better CRC queue stabilization performance with resulting queueing and jitter delays reduction. On the other side, ERICA and EPRCA present high queue standard deviation with high variable sources round trip time and low queue utilization (if the queue goes frequently to zero). Also the QoS perceived by the users is strongly degraded.

V. CONCLUSIONS

We have discussed the opportunity of introducing a cooperative rate control in ATM Network resource management. Firstly we have presented a network queue fluid model to describe the dynamics of the heterogeneous sources accessing to multi-bottleneck network and then we have proposed an ATM cooperative rate control that: i) stabilizes the ATM network once chosen the (feedback and feedforward) controller parameters according to (2) and (3); ii) balances the queue length at a desiderate set point value, reducing packet loss and improving link utilization; iii) is robust to load and round trip time variations; iv) guarantees max-min fair allocation under different static network conditions. The implementation issue of controller has been assessed by using a packet network simulator.

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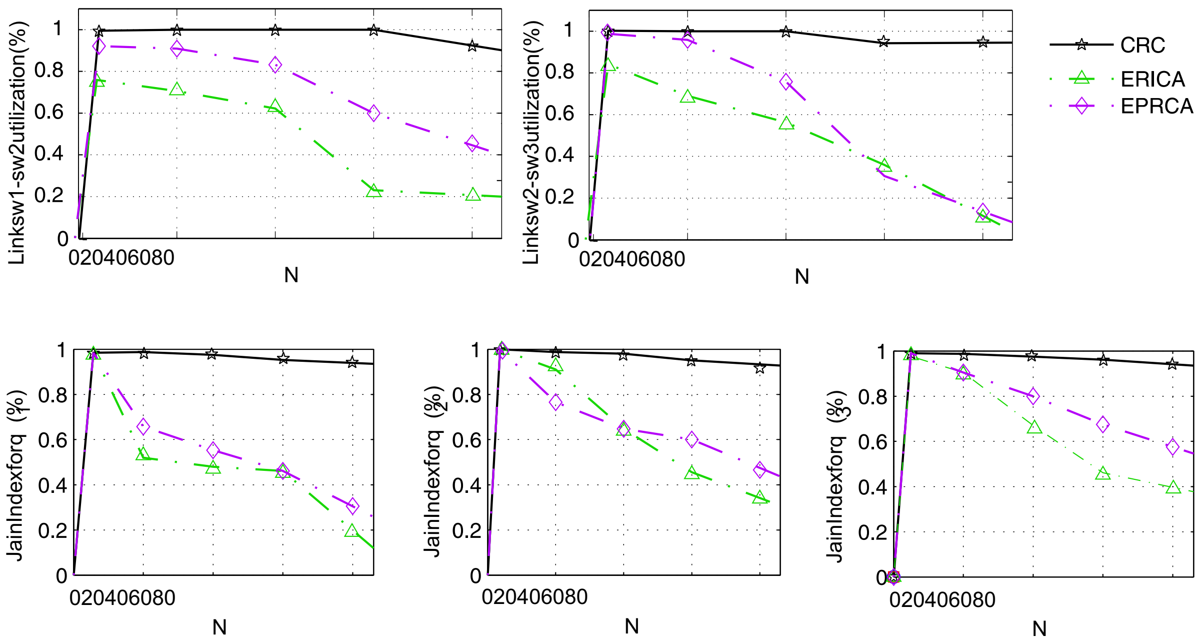

Fig. 3. NIST Experiment - Static Load variations: switches link utilization and Jain index

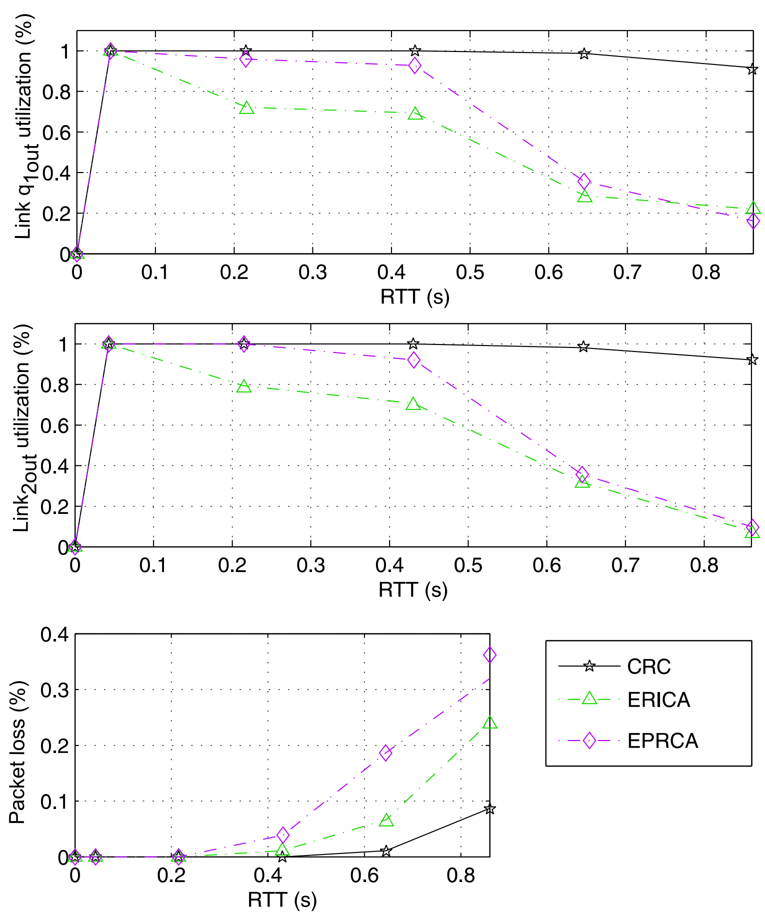

Fig. 4. NIST Experiment - Static RTT variations: swithces link utilization and packet loss