Rate-Based Flow Control Algorithms for High Speed Networks

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Summary

In this project a new control-theoretic framework will be developed for rate-based robust flow controller design for high speed networks, and the algorithms derived from this framework will be adapted for implementation in ATM networks and in the Internet. For this purpose the PIs will collaborate to investigate specific issues arising in their areas of expertise: ATM and Internet flow control, and robust control of infinite dimensional systems.

The mathematical models to be considered in this project are systems with time-varying time-delays. For this class of systems, controller design methods will be developed by investigating several different approaches from $\mathcal{H}^\infty$ control, μ-synthesis, gain scheduling for linear parameter varying systems, and Lyapunov stability theory. In particular, existing gain scheduling techniques for finite dimensional linear parameter varying systems will be extended to time delay systems.

Controllers derived in this framework will be validated by comparing them with the existing controllers designed for ATM traffic management. New flow controllers will also be implemented and tested experimentally. First they will be translated into algorithms to be implemented at the network-layer (switches and routers) within the scope of existing standards. Both connection-oriented networks (e.g. ATM networks) and connectionless networks (e.g. IP based Internet) will be considered in the project. Towards this goal, new techniques will be developed to translate rate-based control solutions into window-based control solutions (especially for applicability in Internet traffic management). The algorithm design will be followed by a performance evaluation using simulation and experimentation to assess the impact of these methods on best-effort services offered to networked multimedia applications. Specifically, experimental techniques will be used to determine network measures of application quality, to be used in simulation studies of these algorithms in representative network configurations.

1 Introduction

High speed networks are networks (and internetworks) which offer high access bandwidth and have a large delay-bandwidth product. The delay-bandwidth product influences the choice of resource management methods used in the network. Flow control is an example of a resource management problem where traditional feedback techniques are being redesigned to handle the high delay-bandwidth product factor.

The terms "flow control," "congestion control" and "traffic management" will be used interchangeably in this proposal to refer to the problem of sharing the available bandwidth (also called available capacity) resource among contending sources, some of which may have special Quality of Service (QoS) requirements. In practice, the contending sources are grouped into classes and each class is controlled separately. This proposal deals with classes which use network feedback (implicit or explicit) to control its sources.

Current feedback schemes may be broadly classified into two groups. The first group uses "rate-based" flow control where sources in the class send data at *rates* regulated through network feedback. The second group uses "window-based" (also called "credit-based") flow control where sources send at most a *window*'s worth of unacknowledged data into the network. The window sizes may be modified based upon network feedback and/or indications of data loss. While this proposal deals primarily with rate-based control, techniques will be developed to translate the rate-based flow control algorithms into window-based frameworks (especially for implementation in the Internet).

There are many algorithms for flow control in high speed networks, see e.g. [4, 7, 9, 10, 11, 31, 49, 50, 51, 59, 87], in particular for ATM networks, e.g. [1, 12, 32, 35, 37, 69, 62, 78]. While most of these algorithms provide analytical arguments to show how they meet desired goals, there is little material in the literature to show how the various approaches are related, and what is a theoretical basis for the problem. In fact, different algorithms are targeted at different sets of goals, which could be unified. Furthermore, the techniques used in these algorithms could be consolidated into a single framework. This is the starting point of the proposed work.

Systems and control theory provides a natural unifying framework for several different algorithms developed for flow control and routing in high speed networks. Initial attempts have been made to develop new flow control algorithms based on recent analysis and design techniques published the systems and control literature, e.g. [19, 49, 63, 87]. Another example of a fruitful collaboration between two researchers whose areas of expertise are networks and control theory, respectively, is demonstrated in a series of papers, [2, 3, 58]. In the same direction, the PIs have recently put the rate-based flow control problem into the framework of robust control of time delay systems, and designed a controller, [55], based on new techniques developed for this class of systems, [22, 75]. In the project these ideas will be extended to develop a new control theoretic framework for rate-based robust flow controller design for high speed networks. Control algorithms to be designed in this framework will be tested via simulations and real-time experiments.

In the next section the current status of ATM rate-based flow control, Internet traffic management, and methods of robust control for time delay systems, are reviewed. Details of the proposed methodology can be found in Section 3. Impact statement of the proposal is in Section 4. The proposed timetable is outlined in Section 5.

2 Prior work

In this section, we highlight the related prior work in areas of ATM rate-based flow control (including a reference algorithm, ERICA), Internet traffic management, and control of time delay systems. The proposal will address certain specific issues in each of these areas.

2.1 Results from Prior NSF Support

We would like to acknowledge that Section 3.1.1 of the proposal (on rate-based flow control system as a time-delay system) is primarily based on our prior work ([55]) with Dr. İftar, whose visit to the US was funded by NSF, Division of International Programs, with award no. INT-9724042. We would also like to mention that Dr. Özbay's prior work in the area of time delay systems (within the framework of repetitive control) was supported by NSF under grant no. MSS-9203418. Although there is no direct connection between flow control for high speed networks, and repetitive control, robust controller design methods, [22, 75, 76], developed from the prior work funded by NSF are applicable to a large class of time delay systems, including flow control for a single battleneck network, as demonstrated in [55].

2.2 ATM Rate-Based Flow Control

The ATM Forum has recently developed a standard for ATM UNI traffic management [5], which specifies a framework for managing the flows of different service classes, and ensures interoperability between equipment from multiple vendors. The Available Bit Rate (ABR) service is one such service which uses a rate-based flow control framework. The sources send data and control cells towards the destination. The switches can modify the control cells (giving feedback) which are returned to the source by the destination along the same path. The standard details the rules for the source and destination end system behaviors, but coarsely specifies the switch behavior. This provides flexibility for various vendors to implement their own switch allocation algorithms. Several switch allocation algorithms have been developed, for example in [1, 35, 69, 62] and in [12, 32, 37, 78], including the ERICA algorithm developed by one of the PIs [36, 37]. The ERICA algorithm is a popular algorithm in the ATM Traffic Management community - in fact the aforementioned standard mentions it as an example reference switch algorithm, [5].

2.2.1 The ERICA Algorithm

The ERICA algorithm will be used as a reference rate-based algorithm in the project, and hence its key features are described here briefly. The algorithm operates at each output port (or link) of a switch. The switch periodically monitors the load on each link and determines a load factor (z), the ABR capacity, and the number of currently active virtual connections or VCs (N). A measurement or "averaging" interval is used for this purpose. The switches use this information to advise the sources about the rates at which they should transmit as follows.

The load factor (z) is the ratio of the measured input rate at the port to the target ABR capacity:

$$z \leftarrow \frac{\text{ABR Input Rate}}{\text{Target ABR Capacity}}$$

where Target ABR Capacity $\leftarrow f(Q) \times$ Total ABR Capacity. The function $f(Q)$ is called the *"queue control function"*, which is used to scale down the total ABR capacity. This function is used to reserve capacity for draining queues under transient conditions, and hence maintain a high bottleneck utilization, while controlling the queuing delay within desirable limits.

The other metrics are used to achieve the max-min fairness goal [12], i.e., to give each source a "maximum possible equal share." Towards this goal, two quantities are calculated, called "VC-Share", and "FairShare:"

$$\text{VCShare} \leftarrow \frac{CCR}{z}, \qquad \text{and} \qquad \text{FairShare} \leftarrow \frac{\text{Target ABR Capacity}}{\text{Number of active Sources}}.$$

ERICA allocates each source the maximum of FairShare and VCShare in every averaging interval. Further, during underload, it allocates each source at least the maximum of the allocations in previous interval. The allocation written in the control cell is the minimum of the calculated Explicit Rate (ER) value and the value already in the cell (possibly written by other switches). The performance of the algorithm depends significantly upon measurement of metrics, and the parameters of the error compensation techniques built into the algorithm. It has been shown through simulations and analytic arguments that this method results in the equalization of the rates and the allocation of the maximum possible rates within the constraints of high utilization and low queuing delays [36, 37].

2.3 Internet Traffic Management

The Internet relies on the TCP/IP protocol suite, combined with router mechanisms to perform the necessary traffic management functions. Applications like file transfer and world wide web servers and clients use TCP as their transport layer. TCP provides reliable transport using a end-to-end window-based control strategy [29]. Specifically, the algorithm increases the source congestion window upon receipt of acknowledgments, but implicitly interprets packet loss as an indication of congestion and resizes the windows controlling transmission.

The TCP congestion control protocol is extremely robust and has been shown to work under pathological conditions. However it has certain drawbacks relating to its performance. First, it is an opportunistic protocol which can result in starvation (unfairness) to connections starting late. Second, its traffic dynamics get considerably complicated if the packet acknowledgments do not arrive in regular intervals, leading to large network queues [86]. Third, sources currently cannot be controlled without actually dropping packets, resulting in retransmission, which is bad for supporting delay-sensitive applications. Fourth, fragmentation and burst drops of packets can result in long timeouts and resetting of window values to initial values leading to drop in utilization [36]. Another drawback seen in mobile and wireless systems is that it confuses error loss, or handoff loss with congestion loss.

The Internet Engineering Task Force (IETF) and independent researchers have proposed several improvements to TCP/IP-based control at the transport and network layers. *Transport layer enhancements* include the fast retransmit and recovery algorithms [71], selective acknowledgments [48] and Explicit Congestion Notification (one bit explicit feedback) [61]. The source procedure (called "slow start") and initialization parameters are also being re-examined to allow more efficient transmission over high-bandwidth satellite links [20].

The IETF and others have also proposed several *network layer* mechanisms for Internet traffic management. This infrastructure also has to be designed to deal with non-responsive flows such as non-TCP best-effort traffic (eg: from UDP/IP applications like IP multicast, network management, and streaming audio/video). It includes mechanisms like scheduling (used to isolate and regulate flows) [17], admission control [83], and packet discard policies (used to enforce fairness) [21, 64]. To support the notions of Quality of Service (QoS) and "real-time" traffic on the Internet, the IETF has also recently developed definitions for premium services (integrated service model) and a signaling protocol (RSVP) [83] which establishes soft reservations for premium service flows. The IETF currently working on a "differentiated services" specification which is a lightweight approach to improve the current "best effort" service and allow implementation of new schemes for accounting and pricing [16]. Pricing itself can be used as a traffic management tool, but its impact is presently unclear [6].

Others, including one of the PIs, have studied the dynamics of TCP/IP over ATM service and the buffer requirements in the center and edges of the ATM network [26, 36]. One significant result of the PI's past work [36, 37] is that with ATM ABR rate control, switch buffer requirements for TCP/IP is a sub-linear function of the number of sources (a scalability property). In other words, the work showed that with ATM ABR rate control it is possible to throttle TCP without incurring packet loss, or allocating huge buffers.

One of the key goals of the proposed work, which is strongly related to the long-term goals and several research projects led by one of the PIs, is to demonstrate the benefits of rate control in non-ATM networks. Specifically, the proposal seeks to translate rate-based control algorithms like

ERICA to augment and enhance the existing end-to-end TCP control. These enhancements can be autonomously implemented at the network layer (routers) without the need for standardization and be transparent to the TCP layer. Also, it will interoperate and complement the other mechanisms surveyed in this section. Providing some form of rate-based control has been a desirable goal for Internet traffic management [16] which would have synergies with other goals like accounting, pricing and regulation. The differentiated services proposal [16] suggests a method for rate control over TCP sources using a combination of enhanced drop policies at the routers and a "profiling meter" at the edge routers which mark packets as "in" or "out" of their negotiated profiles. The key difference is that the approach proposed here will "explicitly" indicate feedback to the sources, compared to the "implicit" mechanism suggested in the "differentiated services" proposal.

2.4 Control-theoretic Approaches for Time-delay Systems

It is well-known that for high speed networks even small propagation time delays may cause very large fluctuations in queue sizes, [10], leading to buffer saturations at the bottleneck nodes. This is due to the phase lag, whose effect on the the stability margins are significant at high flow rates, see e.g. [22]. Hence, one of the most important problems in flow control for high speed networks is to design a controller achieving the largest possible stability margin. Robustness optimization (to maximize various margins of stability) has been investigated for delay systems by several researchers, e.g. [13, 18, 24, 38, 39, 41, 44, 52, 60, 72, 76], including one of the PIs, [76]. In fact, there is rich literature on various problems related to systems with time delays, see for example the books [15, 25, 27, 42, 70] and their references. Many different classes of uncertain time delay systems are also studied in the control theory literature, e.g. [23, 40, 45, 46, 53, 54, 79, 81, 85]. For a survey of recent advances in control of time delay systems see [82].

The main difficulty associated with high speed networks is the uncertainty in time delays in each channel. In the previous work of the PIs, [55], it is assumed that time delays are fixed but unknown; and their nominal values and upper bounds are assumed to be known. An optimally robust controller is designed for this system using $\mathcal{H}^\infty$ techniques, developed earlier by one of the PIs, for delay systems, [75]. A shortcoming of the present approach is that in reality time delays are not fixed, they are varying. Therefore, an important problem identified here is the robust control of systems with varying time delays. A deterministic approach will be pursued here, as opposed to a stochastic framework (e.g. [2, 81]). Many different sufficient conditions are obtained for stability of systems with varying time delays, see for example the results reported in [27, 54, 80]. Most of these sufficient conditions are based on the Lyapunov's second method for functional differential equations, [15, 42].

One possible way to avoid infinite dimensionality in time delay systems is to consider discrete-time version of the problem in state-space, as proposed in [2, 3, 58]. On the other hand, control system analysis and synthesis might be simpler in continuous time by using time-delay terms in tandem, parallel, or feedback connections with finite dimensional operators. For example see controller formulas in [75, 76].

In the proposed study performance optimization will be investigated, with guaranteed stability robustness, for time-varying time-delay systems by extending the existing gain scheduling techniques for Linear Parameter Varying (LPV) systems (see e.g. [56, 65, 67, 84] and their references) to the class of systems appearing in more realistic models of high speed networks. Details of the proposed methodology are outlined in the next section.

3 Proposed Methodology

3.1 A control-theoretic framework for rate-based flow control

3.1.1 Rate-based flow control system as a time-varying time-delay system

In order to outline the basic ideas of the proposed work we consider a single bottleneck network with n source connections, as in [55]. Let $q(t)$ denote the queue length at the bottleneck node at time t, and $r_i(t)$ be the data flow rate assigned to the ith source. The maximum rate at which the ith source can send data will be denoted by d_i; i.e. r_i is restricted to be $r_i(t) \leq d_i$. The rates $r_1(t), \ldots, r_n(t)$ will be assigned to the sources by a feedback controller which measures the queue length, $q(t)$, at the bottleneck node. The capacity is the rate at which data is sent out from the node; it is denoted by $c(t)$. A dynamical model for this system is given by

$$\frac{\mathrm{d}q(t)}{\mathrm{d}t} = \sum_{i=1}^{n} r_i(t - \tau_i(t)) - c(t) \tag{1}$$

where $\tau_i(t)$ is the time delay from the ith source to the bottleneck node. Note that $\tau_i(t)$ is the return-trip delay, which is equal to the amount of time it takes for the feedback control signal to reach the source plus the amount of time it takes for the data to reach the node after it is sent from the source. Depending on physical limitations, and traffic volume in communication channels, $\tau_i(t)$ may be constant or slowly time varying. A block diagram representation of the corresponding feedback control system is shown in Figure 1.

The utilization is defined to be the quantity

$$\rho(t) := \min \left\{ \frac{\sum_{i=1}^{n} r_i(t - \tau_i(t))}{c(t)} \ , \ 1 \right\}.$$

One of the objectives in high speed networks is to keep the utilization as close to 1 as possible. The controller should also achieve "fairness" in steady state, i.e. the rates allocated to different sources should be as close to each other as possible. A trivial choice is then to select equal rates for the sources, with a steady state value c/n, where $c = \lim_{t\to\infty} c(t)$ which is assumed to be non-zero. The above control problem has been solved by the PIs, [55], for the unknown but fixed time delay case. In this project slowly time varying time delay case will be considered.

First the problem will be put in the standard form of the robust control, as shown in Figure 2, where G is the nominal time invariant generalized plant model, K is the controller to be designed,

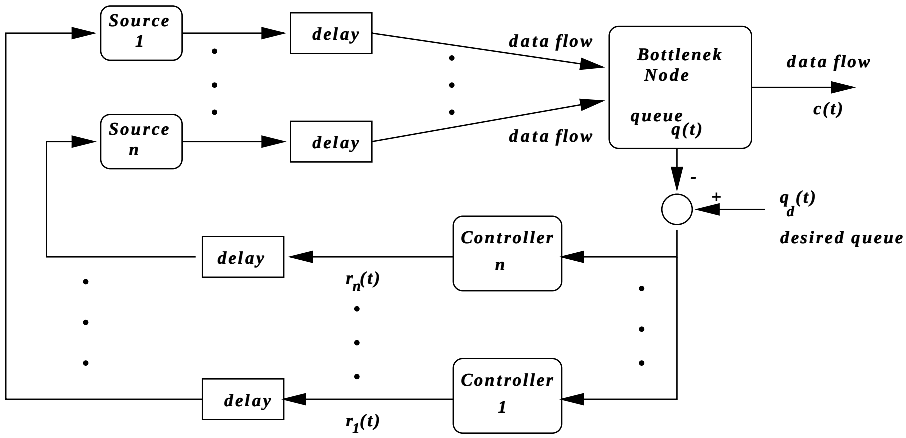

Figure 1: Rate-based flow control system.

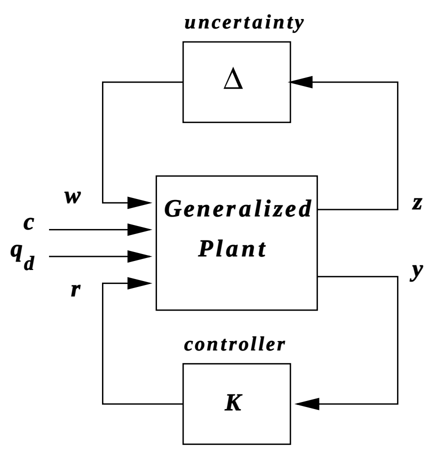

Figure 2: Feedback control system.

and Δ represents time varying time delay uncertainty. The external signals are $c(t)$, and the desired queue length $q_d(t)$. We will initially assume that the controller acts on $y(t) := q_d(t) - q(t)$ and generates $r(t) = [r_1(t) \cdots r_n(t)]^{\mathrm{T}}$.

In this framework it will be assumed that a fixed lower bound h_i can be estimated for each time delay $\tau_i(t)$, i.e.

$$\tau_i(t) = h_i + \delta_i(t)$$

where $\delta_i(t)$ is time varying uncertain part of the time delay. Then the feedback system is defined by the following identities

$$r = K(y) \quad z = M(r) \quad w = \Delta(z) \quad q = P_0([1, \cdots, 1](w + z) - c)$$

where M is $n \times n$ diagonal, and P_0 is scalar, with transfer functions

$$M(s) = \mathrm{diag}(e^{-h_1 s}, \ldots, e^{-h_n s}), \qquad P_0(s) = \frac{1}{s}$$

and Δ is a diagonal linear time-varying operator whose ith diagonal entry is defined by

$$w_i(t) = \Delta_i(z_i(t)) = z_i(t - \delta_i(t)) - z_i(t).$$

Problem 1. Given an upper bound for the magnitude and the derivative of $\delta_i(t)$, for all $i = 1, \ldots n$, find a linear time invariant controller K such that feedback system is robustly stable (i.e. it is stable for all feasible time-varying time delay uncertainties).

A sufficient condition for the existence of a stabilizing controller can be determined from the small gain theorem, see e.g. [34, 73]. According to this theorem if $\|\Delta\| < \varepsilon$ then the feedback system is robustly stable if the closed loop operator from w to z (when Δ loop is broken) is bounded with norm less than $1/\varepsilon$. A simple algebra shows that when Δ loop is broken,

$$z = (I - MKP_0[1, \ldots, 1])^{-1} MK(q_d + P_0 c - P_0[1, \ldots, 1]w). \tag{2}$$

Now the problem reduces to finding a stabilizing linear time invariant controller K for the feedback system (2), whose underlying plant is an unstable multi-input single-output time delay system. We propose to use the skew Toeplitz approach, (Chapter 8 of [22]), to solve this problem, and find a characterization of all robustly stabilizing controllers.

Problem 2. Performance of the feedback system can be measured in terms of the time domain response $q(t)$. For several different choices of desired queue, $q_d(t)$, and possible variations in $c(t)$, $q(t)$ should follow $q_d(t)$. So, among all robustly stabilizing controllers we are interested in finding the ones achieving best performance, i.e. minimizing the error $\|q_d - q\|$. In this part of the project we will define appropriate H^2, and H^∞, based cost functions, and investigate optimal controllers in these frameworks. Also, by developing μ synthesis techniques for the class of time delay systems studied here (and exploiting the special diagonal structure of the uncertainty Δ), it is possible to reduce the amount of conservatism in controller design. In complete generality, for time invariant structured dynamic uncertainty, a polynomial time analysis and synthesis procedure is not available for solution of the structured singular value (i.e. μ) problem; indeed this problem has been shown to be NP-hard, by one of the PIs [77]. Yet, there are numerically efficient algorithms (e.g. D-K iteration) for a conservative version of the μ synthesis problem, where controller is designed from an upper bound of the μ, [57]. Furthermore, it has been shown that, [8, 66, 74], if we allow arbitrarily slow time-varying structured uncertainty (such as the problem considered in the proposed work), then the upper bound becomes tight, and those numerically efficient algorithms solve the robust control problem in a non-conservative fashion. One of the goals of this project is to extend existing algorithms for finite dimensional systems to special types of time delay systems described above.

Problem 3. In the above framework robust stability and performance are achieved for the worst case time delay uncertainty, and the controller to be designed is time invariant. Via identification techniques, and slight modification of the communication procedures between source and the bottleneck (e.g. data packets may contain information about the time they were sent from the source, and this would give the controller exact value of the time delay, in real-time, however feasibility of implementation of such a scheme is yet to be determined) it may be possible to obtain exact values (or estimates) of time varying time delays and sizes of the uncertainties can be reduced. Recall that the controllers designed from Problems 1 and 2 are functions of the delays h_i's and the *a priori* estimate of the uncertainty size ε. By updating these parameters in real time, in the controller expression, it may be possible to improve performance and robustness measures (similar to the framework of [58]). On the other hand, a rigorous stability and performance analysis is necessary for the feedback system where controller is now time-varying. This problem is in the realm of the gain scheduling for linear parameter varying systems (LPV). There are several linear (or affine) matrix inequality (LMI) (or AMI) based optimization techniques for the version of this problem involving finite dimensional systems. In our case the underlying plant is infinite dimensional due to time delays. We propose to investigate extensions of existing techniques for finite dimensional LPV systems to classes of time-varying time-delay system models appearing in high speed networks.

Another possible approach to stability analysis of time-varying time-delay systems is to use Lyapunov theory. This is probably the most popular method used in existing literature. For example, time varying input time delays are considered in [27, 80]; for delayed state systems with input saturation see [54]. The problem considered here contains multiple inputs, with time varying time delays and saturation (which is ignored, except that it can be used in the definition of a cost function, see [55]). The controllers designed from the above defined problems will be tested analytically by using appropriate versions of the Lyapunov stability theory, and the asymptotic stability results of [47].

One of the important objectives of this project is to use the above control-theoretic framework to derive new algorithms for ATM traffic management. In order to demonstrate the basic ideas from control theory we have considered a simple n-source one bottleneck node network model. The problems defined above will be modified if necessary to include specific assumptions and restrictions imposed on the network model.

3.1.2 Deriving Existing and New algorithms for ATM Traffic Management

After the construction of the control-theoretic framework, work will be initiated to correlate existing algorithms like ERICA to this framework. In fact, maintaining this correlation during the development of the framework will be a key objective. Specifically, the project will demonstrate that algorithms like ERICA can be derived as special cases of the framework. More precisely, from Problem 1 defined in the previous section we will obtain a parameterization of the set of all robustly stabilizing controllers. Similar parameterizations will be obtained from solutions of Problems 2 and

3. In this part of the work we will determine whether ERICA (seen as a dynamic controller) falls in any of the classes of the controllers to be derived from Problems 1, 2 and 3.

The previous phase (i.e. deriving existing algorithms as special dynamic controllers which stabilize time-varying time-delay system models corresponding to ATM networks) should indicate a space of undiscovered algorithms which provide other tradeoff points between desired goals and implementation complexity. The performance of these algorithms will be studied and compared with reference algorithms like ERICA.

3.1.3 Algorithms for Internet Traffic Management

An important part of the project is to apply rate-based techniques to complement existing Internet traffic management using window-based control. As a first step, a translation of the ERICA scheme will be demonstrated which will augment existing TCP window-based control. The augmentation will be made in the routers only without necessity of any protocol specification changes. A complete translation of rate-based control to window-based control requires changes at the source end systems (the TCP layer in this case) which is not desirable.

The translation will involve the following steps (the details of which will be studied as part of the proposed work):

a) Determining what granularity of control is required and is feasible in the given environment (one TCP connection, group of TCP connections between the same end points etc).

b) Identifying the equivalent of ERICA metrics which can be measured in routers, and designing approximations if necessary. ERICA requires metrics such as the aggregate input rate, available capacity, individual source rates, and number of contending sources. As an example of the impact of the environment change, note that TCP sources, unconstrained otherwise, can be expected to double their rates initially (slow start phase), and very slowly later (congestion avoidance phase). This information needs to be incorporated into the measurement and control to avoid unnecessary oscillations. Such factors will also influence the choice of robust measurement techniques [37].

c) Calculating an "advertised rate" with an algorithm similar to ERICA which will be used to augment existing TCP control. Specifically, the rate calculated will be enforced as an upper bound on the TCP rate. Since the upper bound can be a little elastic and still be useful, a simplified version of ERICA will be considered for the conversion process (an example of simplification is to eliminate certain metrics and the associated algorithm steps). It should also be noted that the advertised rate information could be derived easily if the TCP connections run on a rate-controlled subnet (e.g. an ATM network with the Available Bit Rate service).

d) Translating "advertised rate" values into equivalent "advertised window" values. One approach is to treat the advertised rate value as an average allocation over the period of the flow's round-trip delay, $\tau_i(t)$, and calculate the window as the product of the advertised rate and the flow's round trip delay. The problem with this approach is that the round trip delays of individual sources are hard (and costly) to measure, and are highly variant (since connections may traverse heterogeneous networks). Further it is unclear whether this scheme is fair: in spite of calculating one advertised rate, different sources get different allocations (based on their respective round trip delays). Another possible translation is to advertise a single window value based upon an upper bound on round-trip delays. However, this could be of limited use if the round-trip times are highly different, and the window values calculated are always larger than the value set by the receiver. Other combinations, predictive schemes and approximations will also be considered. Finally, if different levels of granularity are used (see item a) above), the window values may require additional translation.

e) Transparently conveying this "advertised window" values to contending TCP connections. The goal is to accomplish the overlay of rate-control over TCP control with no modifications (or standardization) required necessary at the source (transport layer). One mechanism identified for this process is to use the receiver window field in TCP acknowledgments, and to readjust the TCP checksum. It should be noted that the proposed mechanism is a violation of the layering concept because the network layer mechanisms manipulate transport layer information. The PIs feel that such a violation can be tolerated if the performance gains are significant.

f) Ensuring the interoperability of routers implementing this scheme with routers which do not implement this scheme. The target scenario is one of routers autonomously choosing whether to implement rate-based control or not. The advertised rate calculated by a single router gives only a partial information about the bottleneck status of the network. In prior work of one of the PIs, [32], it was determined that relying on partial information to direct rate increases could be potentially harmful. However, it is proposed to revisit the problem and consider the implications of the autonomous router implementation model considered above.

From the study of adapting ERICA for window-based control augmentation, it is proposed to develop a methodology (based on some of the ideas sketched above) for conversion of other rate-based schemes into the window-based framework. Specifically, the goal is to allow simple conversion of schemes developed under the control-theoretic framework for Internet traffic management.

3.2 Performance Analysis

A significant piece of the proposal is the performance analysis component, which will proceed in parallel with the design phase, evaluating solutions developed in the previous phase. Further, the performance analysis will also be used investigate the feasibility of such enhanced best effort services to efficiently support networked multimedia applications.

3.2.1 Numerical Implementation

There are commercially available powerful tools for simulation of control systems. In particular, robust controllers based on state space techniques for finite dimensional systems are implemented in related toolboxes of Matlab using numerically reliable methods. However, numerical implementations of robust control algorithms for time delay systems involve several challenging problems (see issues discussed in [22, 75, 76]). A significant effort will be devoted to numerically reliable implementation of the robust controllers to be developed in this project. For this purpose finite dimensional and time delay terms appearing in the controller expression will be separated, (as in [22, 75]) and then model reduction (e.g. balance and truncate) and approximation (e.g. Padé) will be applied to reduce the complexity of the controller without a significant performance degradation.

3.2.2 Experimental Evaluation

An important component of the proposed work is to determine the impact of rate-based techniques implemented in best-effort services on supporting networked multimedia applications. While such applications in general have more quality of service expectations from the network, several tradeoffs between application quality, compression complexity and network service offerings can be made. The incorporation of rate-based techniques provides more control over delay, throughput, and fair distribution of rates [37]. An interesting question is what is the best quality of multimedia applications that can be supported by incorporating rate-based techniques into current best-effort services. Similar questions have recently been posed for the Available Bit Rate (ABR) service in ATM networks [33, 43]. In this project, we will investigate the quality level provided to video applications by rate-based algorithms.

It is proposed to utilize and extend an existing experimental testbed at RPI for studying the performance of current networked multimedia applications. The testbed currently consists of a remote HP 9000 K450 video server accessible though an ATM or Fast Ethernet network (see Figure 3). This heterogeneous multimedia network testbed is a part of the Center for Image Processing Research at RPI and is externally accessible to one of the PIs via an ATM link (connectivity is through the external lines of the ATM switch shown in Figure 3). It is proposed to use two new multimedia workstations connected to an ATM switch forming an ATM network facility connecting to this testbed on the external lines of the ATM switch shown in Figure 3.

The purpose of this experimental stage is to study video applications (like video on-demand, video broadcasts, and video conferencing) to build empirical models of these applications and their quality of service (QoS) requirements. Compressed video (H.261, MPEG-2) as well as uncompressed video will be considered in this stage. This study will result in the building of simulation models and abstraction of performance metrics which will be used to evaluate the rate-based algorithms designed earlier. This algorithm evaluation will then be performed through simulation. The multimedia workstations proposed earlier for experimentation will be converted into simulation servers for the simulation phase.

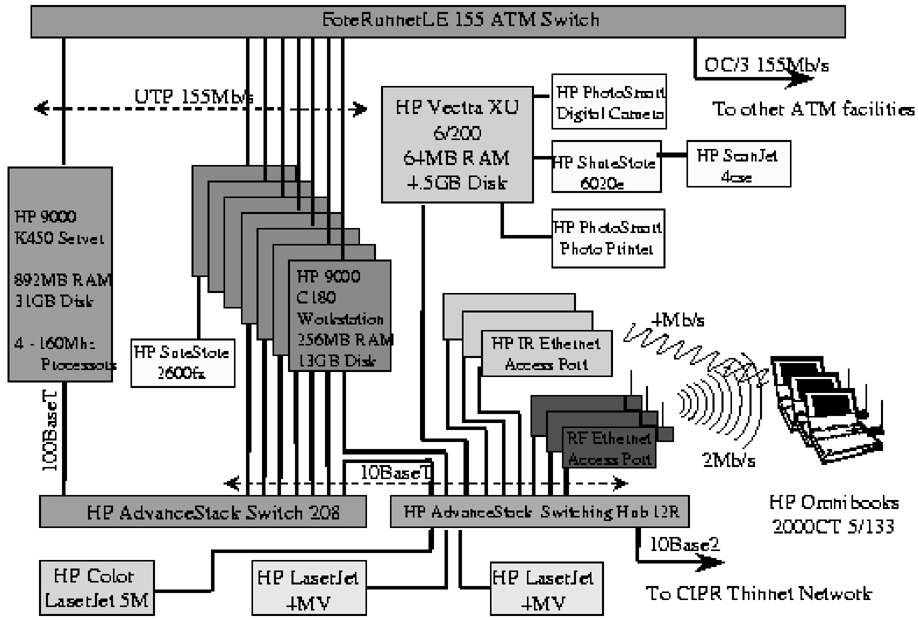

Figure 3: Multimedia Network Testbed

3.2.3 Simulation Evaluation

The simulation phase will use and extend the *netsim* simulation package developed for evaluating the ERICA algorithm models. Simulation will be used as a tool in several of the proposed stages. Initially, it will guide the design and translation of rate-based algorithms into window-based algorithms targeted for enhancing TCP/IP. The algorithms derived for ATM and Internet from the control-theoretic framework will also be evaluated using this procedure. Conventional simulation of rate-based algorithms look at steady state and transient performance using metrics like resource utilization, throughput and queuing delay [36]. The experimental stage described above will result in additional empirical models and metrics. The next important issue is one of choosing the set of simulation experiments. Experimental design techniques [30] will be used to address this issue and control the state space of experimentation.

4 Impact of the Proposed Research

The proposed research is expected to produce theoretical and practical contributions of direct impact and value to the computer networking, telecommunications and controls communities. The traffic management problem in computer networks has proven to be a very complex problem during the design of networking protocols (as evidenced by the several Internet crashes and brown-outs experienced during its growth). It is a problem which has immediate significance due to the exponential growth of the Internet, as well as the variety of applications which are now Internet-enabled, both of which result in the increase in the quantity and heterogeneity of traffic transported by the Internet infrastructure.

A control-theoretic framework of a large class of algorithms like the rate-based algorithms will prove to be of enormous value in designing future traffic management algorithms (for larger ATM switches) without repeating the mistakes of the past. The translation techniques for converting rate-based algorithms into the window based framework will help bridge the gap between the two different approaches. It will also benefit the Internet community immediately by complementing and enhancing the functionality of the current best-effort services without the need for standardization.

The new robust control techniques for time-varying time-delay systems will also be used in intelligent transportation systems. For example, a similar mathematical model appears in the problem of providing automatic steering for autonomous vehicles, [28]. Here, the time delay depends on the speed of the vehicle, which is time-varying. Another potential application of the design methods to be developed is the congestion control in automated highway systems (AHS), since flow control models [14] are the bases for AHS as well.

Robust control of time-delay systems has applications in almost every area of engineering, from manufacturing systems, to chemical process control. Therefore, potential impact of the proposed study is far greater than a few specific examples listed above.

5 Proposed Timetable

The duration of this project will be 3 years. Two PIs (S. Kalyanaraman, and H. Özbay) will be assisted by three graduate research assistants (GRAs). The RPI group, Dr. Kalyanaraman and two GRAs, will mainly work on the ATM and Internet traffic management algorithm realization and the performance analysis (experimentation and simulation) part of the project. They will also interact with the OSU group, Dr. Özbay and one GRA, on the specification/implementation/derivation of the algorithms for ATM and Internet traffic management. These algorithms will be based on the controllers to be developed by the OSU group. Two groups will work as a team in parallel. Main communications will be over the Internet. The PIs are also planning two meetings per year (one at RPI one at OSU). Below is the proposed timetable.

First year: Control theoretic framework for rate based flow controllers.

1.1. Mathematical models of the ATM rate-based flow control system will be obtained as time-varying time-delay processes (RPI and OSU groups). Performance measures will be defined for numerical implementations and experimental evaluations (RPI group).

1.2. Existing rate-based flow control algorithms will be put in the new framework (RPI and OSU groups), and their performance and robustness will be tested analytically (OSU group).

1.3. Translation of the ERICA algorithm into the TCP/IP window-based management will be performed and evaluated by simulation (RPI group).

1.4. Performance and robustness improvement using less conservative approaches, such as LFTs, structured singular value, μ-synthesis, in the controller design (OSU group).

Second year: New techniques and implementation of controller designs.

2.1. Extension of gain scheduling for finite dimensional linear parameter varying systems to time delay systems (OSU group).

2.2 Simulation set-up, and testing. The controller developed earlier by the PIs, [55], will be implemented and its performance will be tested against the reference ERICA algorithm (RPI group).

2.3. Implementation of the flow controller algorithms for the design method developed in 1.4. in the ATM and Internet domains, and its testing via simulation(RPI group).

Third year: New controller design methods and overall evaluation.

3.1 Continuation of 2.1., and new algorithms using Lyapunov theory and investigation of adaptive implementations (OSU group).

3.2. Implementation of the algorithms developed in 2.1., and 3.1., and overall evaluation of the methods investigated in this project (RPI group).

3.3. Final report (RPI and OSU group).

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M.Eng., McGill University, Montréal, Québec, Canada, 1987
B.Sc., Middle East Tech. University, Ankara, Turkey, 1985

Academic Employment History:

10/94 – present: Associate Professor, Dept. of Electrical Eng., Ohio State Univ., Columbus OH.
1/91 – 9/94: Assistant Professor, Dept. of Electrical Eng. Ohio State Univ., Columbus OH.
6/94 – 8/94: NASA/OAI Summer Faculty Fellow, NASA Lewis Research Center, Cleveland OH.
9/89 – 12/90: Assistant Professor, Dept. of Electrical Eng., Univ. of Rhode Island, Kingston RI.
9/87 – 8/89: Graduate Assistant, Dept. of Electrical Eng., Univ. of Minnesota, Minneapolis MN.
8/85 – 5/87: Graduate Assistant, Dept. of Electrical Eng., McGill Univ., Montréal PQ, Canada.

Academic Awards:

1994 Lumley Research Award, and 1996 Annual Research Accomplishment Award, College of Engineering, The Ohio State University.

Sponsored Research (current and past 5 years):

Funded by *The Ohio State University*, *Air Force Office of Scientific Research*, *NASA Lewis Research Center*, and *National Science Foundation*.

Service:

Senior member of IEEE and its Control Systems Society.
Associate Editor, *IEEE Transactions on Automatic Control.*

Selected Publications:

1. C. Foias, H. Özbay, A. Tannenbaum, *Robust Control of Infinite Dimensional Systems: Frequency Domain Methods*, Lecture Notes in Control and Information Sciences, No. 209, Springer-Verlag, London, 1996.

2. O. Toker and H. Özbay, "Complexity issues in robust stability of linear delay-differential systems," *Mathematics of Control, Signals, and Systems*, vol. 9 (1996), pp. 386–400.

3. O. Toker and H. Özbay, "H^∞ Optimal and suboptimal controllers for infinite dimensional SISO plants," *IEEE Transactions on Automatic Control*, vol. 40 (1995), pp. 751–755.

4. O. Toker and H. Özbay, "Gap metric problem for MIMO delay systems: Parametrization of all suboptimal controllers," *Automatica*, vol. 31 (1995), pp. 931–940.

5. H. Özbay, "H^∞ optimal controller design for a class of distributed parameter systems," *International Journal of Control*, **58** No. 4, October 1993, pp. 739–782.

6. M. Zeren and H. Özbay, "On the synthesis of stable H^∞ controllers," to appear in *IEEE Transactions on Automatic Control*; a preliminary version is in *Proc. of the American Control Conference*, Albuquerque NM, June 1997, pp. 1302–1306.

7. T. E. Peery and H. Özbay, "H^∞ Optimal repetitive controller design for stable plants," *Transactions of the ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 119 (1997), pp. 541–547.

8. H. Özbay and G. R. Bachmann, "H^2/H^∞ Controller design for a 2D thin airfoil flutter suppression," *AIAA Journal of Guidance Control & Dynamics*, **17**, (1994), pp. 722–728.

9. H. Özbay and J. Turi, "On input/output stabilization of singular integro-differential systems," *Applied Mathematics and Optimization*, vol. 30, 1994, pp. 21–49.

10. K. Lenz and H. Özbay, "Analysis and robust control techniques for an ideal flexible beam," in *Multidisciplinary Engineering Systems: Design and Optimization Techniques and their Applications, (Control and Dynamical Systems, vol.57)* C. T. Leondes ed., Academic Press Inc., 1993, pp. 369–421.

List of collaborators (last 48 months):

At The Ohio State University:
C. Hatipoğlu, H. Hemami, Ü. Özgüner, R. Richardson, S. Rokhlin, T. B. Şahin, K. Srinivasan.

Other Institutions:
V. Eldem (TUBITAK, Turkey), C. Foias (Indiana U.), S. Garg (NASA Lewis), C. Gu (Cal. Poly. State Univ.), A. İftar (Anadolu U., Turkey), S. Kalyanaraman (Rensselaer Polytech. Institute), K. Lenz (U. Minnesota, Duluth), K. Özçaldıran (Boğaziçi U., Turkey), J. Turi (U. Texas, Dallas).

List of advisees and post-docs:

T. E. Peery, PhD, (Texas Instruments), O. Toker, PhD, (King Fahd U., Saudi Arabia), and M. Zeren, graduating PhD student.
Post-doc: K. Ünyelioğlu.
M.S. Students graduated: G. Bachmann, A. C. Bailey, O. Toker, C. Ulus, M. B. Uzman, J. Yang.

MS Thesis Advisor: Carla A. Schwartz, now with MathWorks Inc, Natick MA.

PhD Thesis Advisor: Allen Tannenbaum, U. Minnesota, Minneapolis MN.

Budget Justification for RPI's Participation

The budget of this project is based on the above mentioned personnel and timetable. Four weeks of summer support and 10% academic year release time is requested for Dr. Kalyanaraman for each year.

Two graduate research assistants (two PhD students) will work under Dr. Kalyanaraman's guidance at Rensselaer Polytechnic Institute for three years (including summers). The additional student support is requested due to the increased load of experimental, simulation work, and standards activity (in ATM Forum and Internet Engineering Task Force) during the course of project.

The equipment required for the RPI's part of this project consists of two multimedia workstations and one ATM switch. The workstations will be connected by the ATM switch to access and utilize other multimedia testbed facilities available at RPI. The workstations will be used to conduct both experimental work as well as act as computational servers for simulation. RPI will cost-share a total of $40,000 in cash, which is approximately 10% of the RPI portion of the budget. This cash will be used to purchase the two multimedia workstations.

Travel budget includes once a year travel to OSU (Columbus, OH) for meetings between the PIs, one trip to a major control conference per year, and one trip each to selected IETF and ATM forum meetings (to disseminate ideas among implementors and to address standardization issues).

Budget Justification for OSU's Participation

One month summer support and 10% academic year release time is requested for Dr. Özbay for each year.

One graduate research assistant (a PhD student) will work under Dr. Özbay's guidance at The Ohio State University for three years. Tuition and fees of this GRA will be waived by OSU as cost-sharing, this is equivalent to $23,524 for three years.

The equipment required for the OSU's part of this project consists of two workstations with internet connections and connections to a CD-ROM and a printer. Software packages for control system design and simulation will be installed on the workstations.

Travel budget includes once a year travel to RPI (Troy, NY) for meetings between the PIs, and one trip to a major control conference per year.

Budget Guidelines

(a) summer support (1 month each PI)

$7,461 for one month per year for OSU PI

$6,867 for four weeks per year for RPI PI

(b) 10% academic year release time for each PI

$6,715 per year for OSU PI

$6,160 per year for RPI PI

(c) student support: 2 students for RPI PI (tuition + stipend), and 1 student for OSU PI (stipend only, tuition is waived)

$16,200 per year for one (1) OSU GRA

$60,208 per year for two (2) RPI GRAs

(d) fringe benefits:

(OSU): ($1,336 + $1,585 + $194) = $3,115 per year

(RPI): (at 32%) = $4,169 per year

(e) equipment and software $75,000

2 multimedia workstations (for simulation and experimental work, $20,000 ea) for RPI PI

1 ATM switch ($20,000) for RPI PI.

1 workstation and software for OSU PI, controller design, simulation and testing ($15,000)

(f) travel:

$6,000 per year ($2,000 each for RPI PI and OSU PI) for conferences and travel between Columbus and Troy (once a year) plus $2,000 for RPI PI for selected IETF and ATM forum meeetings.

(g) publishing and dissemination costs:

$1,000 per year

(h) cost sharing for equipment:

A total of $ 40,000 cash (which would cover two workstations)
OSU cost shares by covering the tuition of the GRA (a total of $23,524)

(i) total direct costs: total of the above (a) through (g) minus (h)

(j) indirect costs

OSU rate is 46% of OSU's share of (i)-(e)

RPI rate is 54% of RPI's share of (i)

(k) total (i) + (j)