

Robust Control and Rate Coordination for Efficiency and Fairness in ABR Traffic with Explicit Rate Marking¹

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Abstract

The problem of efficiency and fairness of ABR (Available Bit Rate) traffic with explicit rate marking is investigated from a control point of view. It is revealed that due to significant uncertainty on time delays in ABR traffic and strong interaction among switches, ABR traffic imposes a great challenge to control strategy development. Focusing on robustness of traffic control and asymptotic fairness, we propose a new control strategy that employs robust control to accommodate delay uncertainty and rate coordination for fairness. Conditions are presented under which robust stability and convergence are guaranteed.

1 Introduction

In this paper, the problem of efficiency and fairness of ABR traffic with explicit rate marking is investigated from a control point of view. Taking typical network environments into consideration, we focus on the generic features, essential issues, and potential control strategies arising in such problems. Focusing on robustness of traffic control and asymptotic fairness, we propose a new control strategy that employs robust control methodologies to deal with uncertain time delays on connections and switches, and performs rate coordination to provide fairness among connections while achieving high efficiency.

1.1 ABR Traffic

The ATM Forum Traffic Management Specification Version 4.1 [2] defines various ATM service categories. Among these, available bit rate (ABR) service was created for data communications that are relatively delay-insensitive but are sensitive to data loss. As the name implies, ABR connections receive the bandwidth that has not been assigned to constant bit rate (CBR) connections and is not currently used by variable bit rate (VBR) connections. The available bandwidth must be allocated “fairly” among the ABR connections. The actual amount of bandwidth an ABR connection receives depends on information exchanged among the source, destination, and switches along the path from the source to the destination. This information is provided to the source using rate-based closed-loop feed-

back control. Typically, feedback is provided in specific fields of the resource management (RM) cells that are periodically transmitted by the source for the express purpose of obtaining feedback. The algorithm employed by the switch to provide this feedback is implementation-dependent, but uses one of three techniques: EFCI marking, relative rate marking, or explicit rate marking.

Explicit rate marking, which is the scheme of choice in most current ATM switches and in this paper, uses the explicit rate (ER) field of the RM cell to specify an exact rate at which the source should send data. This scheme, although more complex in implementation than the other two schemes, provides more precise information to the source and enhances flexibility in designing control algorithms.

1.2 Main Issues and Basic Approaches

ABR traffic imposes a great challenge to control strategy development, partially due to the following factors: (1) Delay times of network channels differ greatly among different connections and vary with time. (2) Fairness is a global property of ABR networks and requires coordination among switches and sources. However, global information on fairness is not available to individual switches. (3) The goal of queue control at switches for maximizing network utility and minimizing cell loss, and the goal of fairness often conflict when network conditions are changing. (4) Since ABR traffic relies on available bandwidth, variations in available bandwidth can be large and unpredictable.

Our approach in dealing with these issues can be summarized as follows: Robust controllers are first designed for local queue control. The design guarantees local robust stability, and fast response of sending rates to variations in available bandwidth in the presence of unknown channel time delays. Second, a fairness algorithm is devised which calculates desired bandwidth distribution for each connection with fairness as its objective function. During transient network conditions, the actual control action is a weighted combination of queue control and fairness control. The weighting function is then adapted based on an indicator of network traffic conditions. The indicator reflects essentially the speed of traffic pattern changes. When the traffic pattern is changing dramatically, the control action is more

¹This research is supported in part by NSF Grant ECS-9634375.

inclined to queue control to maintain system stability and tracking performance. When the traffic pattern is relatively smooth, fairness coordination becomes more dominant. If certain conditions on robust controllers, traffic patterns, and the appropriate selection of coordination mechanisms are met; we show that this coordination leads to a stable system with asymptotic fairness, fast response, and robustness.

1.3 Related Work

The feedback structure of ABR network systems strongly suggests a potential utility of feedback control theory in analyzing system behavior and designing efficient and robust network control algorithms. Substantial efforts have been devoted to this pursuit [1, 9, 13, 15, 18]. Fair share algorithms have been developed in [3, 4, 5, 8, 6, 11, 7, 10, 14]. The primary objectives of these algorithms are high utilization and fair share of the available bandwidth.

In this paper, it is demonstrated that the control issues inherent in ABR traffic are both non-standard and non-trivial. Rigorous analysis of stability and convergence to an efficient and fair operating point is then carried out for ABR traffic control systems in the presence of variable time delays and including the interaction between queue control and fairness.

2 Problem Formulation

An ATM network consists of sources, switches, and destinations. Due to variations in other higher priority network traffic, such as CBR and VBR, an ABR connection experiences significant uncertainty on the available bandwidth during its operation. In principle, it is highly desirable that sources can adjust their sending rates promptly to accurately track their assigned bandwidth so that the network utility can be maximized without cell loss. We assume in this paper that at the time of connection establishment the switch sets up a virtual buffer for internal routing of each connection's ATM cells. The data stored in the buffer forms a queue which smoothes out differences between the input and output rates of data transmission. One goal of control design is to maintain a desirable queue size that reflects a tradeoff among network efficiency, buffer delay, and cell loss.

2.1 Models

Suppose that at time t , a typical switch, SW , has n input ABR connections and the same number of output connections. Denote these immediate sources, which may be a source or another switch, by S_1, \dots, S_n . Let $r_i(t)$ be the sending rate of source S_i at time t , for $i = 1, \dots, n$. Due to network delays, the arrival rate of the i^{th} connection, $x_i(t)$, at switch SW is related to r_i by $x_i(t) = r_i(t - \tau_i^f)$, where τ_i^f is the time delay for connection i in the forward direction. The output rates at SW will be d_1, \dots, d_n , which may go to a destination or another switch.

The queue size of the i^{th} connection at time t is $q_i(t)$.

The dynamic equation of the queue for the i^{th} connection at the switch is simply $\dot{q}_i(t) = x_i(t) - d_i(t)$. To maintain high network utility and low cell loss ratios, one designates a desired queue size q_i^0 . q_i^0 is determined on the basis of switch structures, buffer sizes, delays on connections, typical traffic patterns, and variations in available bandwidth.

The first goal of ABR traffic control is to ensure that $q_i(t)$ is close to q_i^0 , namely reducing the error $e_i = q_i - q_i^0$. The error dynamics are

$$\dot{e}_i(t) = \dot{q}_i(t) = x_i(t) - d_i(t) = r_i(t - \tau_i^f) - d_i(t).$$

The input-output relationship of the i^{th} connection can also be expressed in the frequency domain as

$$E_i(s) = \frac{1}{s}(e^{-\tau_i s} R_i(s) - D_i(s)) = P_i(s)R_i(s) - \frac{1}{s}D_i(s)$$

where $P_i(s) = \frac{1}{s}e^{-\tau_i s}$.

The control action u_i , the explicit rate for the i^{th} connection sent from the switch, is generated at the switch based on a certain design methodology defined later in the paper. Structurally, u_i may be designed as a function of e_i (feedback), d_i (feedforward), and other traffic information (coordination) $u_i = u_i^T + u_i^c$, where $u_i^T = f_i(e_i, d_i)$ is the component for queue control and u_i^c is the component for coordination with other switches for fairness. If one is to use linear time-invariant controllers for queue control, u_i^T will have the structure $U_i^T(s) = -F_i(s)E_i(s) + K_i(s)D_i(s)$. Upon applying the feedback u_i^T the i^{th} connection will have a closed-loop system expressed by

$$E_i(s) = \frac{e^{-\tau_i s} K_i(s) - 1}{s + e^{-\tau_i s} F_i(s)} D_i(s).$$

Although the information on fairness is not available to individual switches, connections that are bottlenecked elsewhere in the network will leave some assigned bandwidth unused at this switch. This information is first sent back to the sources via RM cells and then propagates among the routes to other switches as indicated by lower actual sending rates than assigned bandwidth. Mathematically, if the i^{th} connection is bottlenecked with peak rate c_i , its sending rate can be modeled as a saturation node of value c_i

$$r_i(t) = \max\{\min\{u_i(t - \tau_i^b), c_i\}, 0\} := S(u_i(t - \tau_i^b)),$$

where τ_i^b is the time delay from the time u_i is sent from the switch to the time the information of a bottleneck becomes available to the switch. This bottleneck leads to unutilized network resources. As a result, rate coordination will be performed on the basis of this saturation information.

3 Control Structures and Strategies

ABR traffic control imposes multiple control objectives. First, for each individual switch and route it is desirable that the sending rate matches closely and promptly the assigned bandwidth so that network resources can be optimally utilized. Second, to avoid

cell loss and enhance smooth data transmission, certain queue sizes must be maintained. Finally, to achieve fairness among connections, assigned bandwidths must be adjusted dynamically based on distributions of available bandwidth over the network.

3.1 Stability and Tracking in Queue Control

Queue control at a switch aims at the reduction of e_i (queue stability) and $x_i - d_i$ (error tracking). In this paper, we assume that available bandwidth variations are large below a given frequency bound ω_M and small beyond that. Consequently, reduction of $x_i - d_i$ is to be achieved satisfactorily over the frequency band $[0, \omega_M]$. This requirement can be expressed conveniently by defining a stable weighting function, $W(s)$, whose gain spectrum, $|W(j\omega)|$, is close to 1 in the band $[0, \omega_M]$ and decreases quickly outside it. As a result, the design problem becomes the reduction of

$$\|W(X_i - D_i)\|_\infty = \left\| W \frac{e^{-\tau_i s} K_i - 1}{1 + P_i F_i} \right\|_\infty.$$

F_i and K_i can be designed by using either the classical PID and lead-lag compensation, or H^∞ optimization. It is observed that $K_i(s)$ is a feedforward mapping and does not affect stability. It follows that one may select a stabilizing feedback $F_i(s)$ first. For instance, if $F_i(s) = k$, a gain feedback, then the standard Nyquist stability analysis leads to the stability condition $k < \frac{\pi}{2\tau_i}$. After the selection of $F_i(s)$, $K_i(s)$ can then be designed to reduce or minimize $W(s) \frac{e^{-\tau_i s} K_i(s) - 1}{1 + P_i(s) F_i(s)}$.

3.2 Fairness

To achieve fairness, one must consider the interactions among the connections. We assume that the information on whether a connection is bottlenecked or not can be obtained after a certain time delay. In particular, if the measured rate $x_i(t) = c_i < u_i(t - \tau_i) - \delta$ where δ is a threshold value, then we label the i^{th} connection as bottlenecked with saturation value c_i . Due to the time-varying nature of ATM networks, c_i will vary with time. Assume that the ABR bandwidth of the switch at time t is $B(t)$. At time t , assume that m connections, say, r_1, \dots, r_m , are bottlenecked with saturation values $c_1(t), \dots, c_m(t)$, respectively. A commonly used algorithm for distributing bandwidth can be described as follows: Let

$$a(t) = \frac{B(t) - (c_1(t) + \dots + c_m(t))}{n - m}.$$

The fair share functions for the connections are then defined by $f_i(t) = c_i(t)$, $i = 1, \dots, m$; and $f_i(t) = a(t)$, $i = m + 1, \dots, n$. For fairness, it is desirable that $r_i(t)$ remains close to $f_i(t)$ for all t , or at least, asymptotically as $t \rightarrow \infty$. Note that $f_i(t)$ is always bounded by $B(t)$.

It can be shown that at steady state when the available bandwidth remains constant, this locally executed algorithm will lead to a convergence to max-min fairness. The reader is referred to [8, 11] for further details. However, the main issue here is the interaction between

queue control and fairness algorithms. What is the impact of fairness algorithms on the stability of queue control? Will convergence to fairness remain valid when queue control is continuously in operation? How should one decide whether to use queue control or fairness algorithms to generate control actions? These will be answered in the subsequent sections.

3.3 Coordination of Traffic Control and Fairness

The objectives of queue control and fairness coordination often conflict during dynamic transient network conditions, e.g., when the output rates d_i vary significantly with time. Consequently, a tradeoff must be retained in deciding control actions. Our algorithms for determining the total control actions can be summarized as follows. Let $U_i^T(s) = -F_i(s)E_i(s) + K_i(s)D_i(s)$, $i = 1, \dots, n$, be the control action based on dynamic queue control of the i^{th} connection. At time t , the total control action, $u_i(t)$, will be determined by

$$u_i(t) = \alpha(t)u_i^T(t) + (1 - \alpha(t))f_i(t), \quad i = 1, \dots, n.$$

where $0 \leq \alpha(t) \leq 1$. The special case $\alpha = 1$ represents control actions for traffic control only; the opposite extreme case $\alpha = 0$ indicates pure fairness assignment of available bandwidth.

One of the most important issues here is the selection of the weighting $\alpha(t)$. The OSU Scheme [8] proposes that one specifies a transient phase in which $\alpha = 1$ and afterwards switches to the static phase with $\alpha = 0$ for fairness. The main drawback of this approach is that it is very difficult to specify such phases since network traffic seldom settles down to an equilibrium point [12]. In this paper, we introduce an indicator of traffic pattern variations and use that indicator to tune $\alpha(t)$ smoothly. Generically, the indicator is a function of the output rates $d_i(t)$ and ABR target bandwidth $B(t)$, $g(t) = G(d_i, B)$. Typical examples include

$$G(d_i, B) = \frac{b_1 s}{s + b_2} d_i + \frac{c_1 s}{s + c_2} B. \quad (1)$$

Then $\alpha(t) = \frac{|g(t)|}{a + |g(t)|}$, where $a > 0$ is a scaling factor. Note that in this expression, $0 < \alpha(t) < 1$.

4 Stability and Convergence

In this section, we present the main theoretical results of this paper on stability of the total system and conditions under which convergence to fairness is guaranteed.

4.1 Robust Stability and Redesign of F_i

Although we have established stability when the control action is determined solely on the basis of traffic control, the modified strategy with fairness consideration potentially leads to instability. In Theorem 1, we provide a condition for redesigning controllers under which stability is guaranteed even when coordination for fairness is used.

The modified control action results in the following feedback system: $u_i(t) = \alpha(t)u_i^0(t) + (1 - \alpha(t))f_i(t)$. Since α is time varying, the network and controllers are time-varying systems. For stability analysis, define the open-loop system $M = P_i F_i$.

Theorem 1 *Suppose that the time delay $\tau_i \leq \bar{\tau}_i$ and $f_i(t)$ is bounded. If F_i satisfies: (1) F_i robustly stabilizes P_i for all $\tau_i \leq \bar{\tau}_i$, (2)*

$$\sup_{0 < \tau_i \leq \bar{\tau}_i} \|M(1 + M)^{-1}\|_\infty \leq 1,$$

then, the closed-loop system is robustly stable for all time varying $\alpha(t)$ with $0 < \alpha(t) < 1$ and $0 < \tau_i \leq \bar{\tau}_i$.

Proof: Since F_i stabilizes P_i , the closed-loop systems with $\alpha \equiv 1$, $(1 + M)^{-1}$ and $M(1 + M)^{-1}$ are stable with $\mu = \|M(1 + M)^{-1}\|_\infty < \infty$. Observe that when $\alpha(t)$ is inserted into the loop, we have

$$1 + \alpha M = 1 + M + (\alpha - 1)M,$$

with $|\alpha - 1| < 1$. It follows that

$$(1 + \alpha M)^{-1} = (1 + M)^{-1}(1 + (\alpha - 1)M(1 + M)^{-1})^{-1};$$

$$M(1 + \alpha M)^{-1} = M(1 + M)^{-1}(1 + (\alpha - 1)M(1 + M)^{-1})^{-1}$$

By the Small Gain Theorem [17, 16] and the fact that $|\alpha - 1| < 1$, the closed-loop system will remain stable for all $0 < \alpha < 1$ if $\mu = \|M(1 + M)^{-1}\|_\infty \leq 1$. \square

The conditions of Theorem 1 can be used to redesign F_i so that coordination for fairness will not destabilize the overall system. The redesign of F_i can be done by classical lead-lag design on Bode plots or by H^∞ design for optimal solutions.

4.2 Convergence to Fairness

Fairness requires that the rates at the switches reach their fair share values when network traffic patterns settle to their steady states. More precisely, assume that $\lim_{t \rightarrow \infty} B(t) = B$, $\lim_{t \rightarrow \infty} c_i(t) = c_i$, $i = 1, \dots, m$. Then $\lim_{t \rightarrow \infty} a(t) = \frac{B - (c_1 + \dots + c_m)}{n - m} := a$. Consequently, the limiting fairness is given by $f_i = c_i$, $i = 1, \dots, m$; $f_i = a$, $i = m + 1, \dots, n$.

Theorem 2 *If (1) F_i is designed to satisfy the conditions of Theorem 1; (2) $d_i(t)$ is uniformly bounded; (3) $\alpha(t) > 0$ and $\lim_{t \rightarrow \infty} \alpha(t) = 0$, then $\lim_{t \rightarrow \infty} x_i(t) = f_i$.*

Proof: Observe that the traffic control signal u_i^0 is given by

$$u_i^0 = -F_i e_i + K_i d_i = (-F_i M_1 + K_i) d_i - F_i M_2 f_i.$$

By the hypotheses and Theorem 1, the closed-loop system is robustly stable for any $0 < \alpha(t) < 1$ and $\tau_i \leq \bar{\tau}_i$. Hence, both $F_i M_1 + K_i$ and $F_i M_2$ are bounded operators. It follows that u_i^0 is uniformly bounded, since both $d_i(t)$ and $f_i(t)$ are uniformly bounded, $|u_i^0(t)| \leq b < \infty$. As a result, $\lim_{t \rightarrow \infty} |\alpha(t)u_i^0(t)| \leq b \lim_{t \rightarrow \infty} |\alpha(t)| = 0$. This implies that

$$\lim_{t \rightarrow \infty} |u_i(t) - (1 - \alpha(t))f_i(t)| = 0,$$

or $\lim_{t \rightarrow \infty} u_i(t) = \lim_{t \rightarrow \infty} f_i(t) = f_i$, since $\lim_{t \rightarrow \infty} \alpha(t) = 0$.

Finally, since $x_i(t) = u_i(t - \tau_i)$, $\lim_{t \rightarrow \infty} x_i(t) = \lim_{t \rightarrow \infty} u_i(t) = f_i$, namely, the rates become asymptotically fair. \square

5 Simulation Results

To demonstrate the design methodologies introduced in this paper, we perform simulations on a network with four switches and four sources as shown in figure 1. Matlab/Simulink is used to simulate the switch dynamics and delays on connections. To understand the robustness of the controlled system, the connections in figure 1 have different time delays. The exact values of time delays are not used in design. But rather their upper bounds are used to design controllers which can provide robustness against all possible delays within the bounds. For example, we assume that the actual delay time of the connection between source 1 and switch 1 is bounded by 0.1 second, which is used to design the feedback controllers.

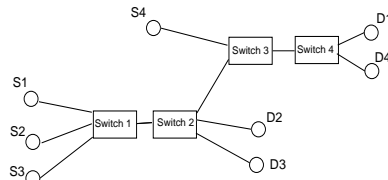


Figure 1: An Example of ABR Network

In this simulation, for each connection i , F_i is a gain feedback $F_i = K_p$. It is easy to verify that if the maximum time delay for the connection is $\bar{\tau}_i$, then $K_p < \frac{\pi}{2\bar{\tau}_i}$ will guarantee robust stability for all $\tau_i \leq \bar{\tau}_i$ without fairness coordination. However, to satisfy the condition of Theorem 1,

$$\sup_{0 < \tau_i \leq \bar{\tau}_i} \|M(1 + M)^{-1}\|_\infty \leq 1, \quad (2)$$

the gain must be further confined.

For example, for the maximum delay of $\bar{\tau}_i = 0.1$, robust stability against delay uncertainty requires that $K_p < 15.708$. The corresponding $\|M(1 + M)^{-1}\|_\infty = 2.327$, violating the condition of Theorem 1. By reducing K_p to 5, the norm condition (2) is satisfied. For the selected K_p , feedforward K_i is to be designed to reduce

$$W(s) \frac{e^{-\tau_i s} K_i(s) - 1}{1 + \frac{1}{s} e^{-\tau_i s} K_p} = W_0(s)(K_i(s) - e^{-\tau_i s}) \quad (3)$$

Since $|W_0(j\omega)|$ is very small outside $[0, \omega_M]$, reduction of (3) amounts essentially to approximation of $e^{-\tau_i s}$ by a causal $K_i(s)$ in the frequency band $[0, \omega_M]$. Although the problem can be solved optimally by H^∞ optimization, the optimal solution will be an infinitely dimensional controller. To obtain a solution of low-order K_i , we will perform parametric optimization for simple K_i .

For instance, let $\omega_M = 20$ (radian/sec) and $\bar{\tau}_i \omega_M < \frac{\pi}{2}$.

(1) $K_i(s) = k$. In this case, we consider

$$\max_{\omega \in [0, \omega_M]} |k - e^{j\bar{\tau}_i \omega}| = (k^2 - 2k \cos \bar{\tau}_i \omega_M + 1)^{\frac{1}{2}}.$$

Hence, k can be selected by $\min_k (k^2 - 2k \cos \bar{\tau}_i \omega_M + 1)$, which is solved as $k = \cos \bar{\tau}_i \omega_M$. For $\bar{\tau}_i = 0.05$ and $\omega_M = 20$, $k = 0.5403$.

(2) $K_i = k \frac{s+a}{s+b}$, $k > 0$, $a > 0$, $b > 0$. Similar to the first case, we are seeking

$$\min_{k > 0, a > 0, b > 0} \max_{\omega \in [0, \omega_M]} \left| k \frac{j\omega + a}{j\omega + b} - e^{j\bar{\tau}_i \omega} \right|$$

A computer search can be performed to find the optimal parameter values.

In this simulation, we assume that the ABR for the connection between Switch 1 and Switch 2 initially varies with time and eventually settles to a steady state value of 150 (K cell/second). Similarly, the ABR for the connection between Switch 3 and Switch 4 eventually settles to 140. It is easy to check that at the steady state, the fairness is achieved if the source rates are $S1 = 50$, $S2 = 50$, $S3 = 50$, $S4 = 90$. The threshold for all queues is set to 30 and initial queue sizes are set to values different from their thresholds.

Simulation results are presented in figure 2. It is observed that under the control strategies introduced in this paper, after a stable dynamic transient process, the transmission rates of sources converge to their fair share values.

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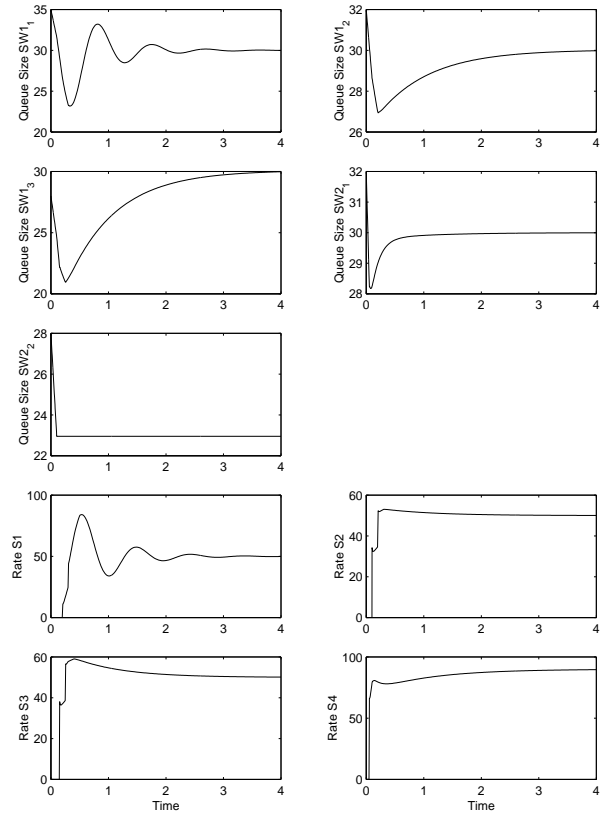


Figure 2: Simulation for Stability and Fairness (Rate: K cell/second; Time: second)

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