A Parallel Control Scheme for ABR Services in ATM Networks

Q. L. Ding and S. C. Liew

Abstract: **This paper proposes a new scheme –** ***parallel control scheme with feedback control (PCFC)*** **for ABR services in ATM networks. The information from a source is split into a number of streams, for delivery over separate parallel connections with particular coding. At the receiver, the original information is reconstructed by the received packet from the parallel connections. The effects of PCFC on the network performance are due to two factors: Traffic splitting and load balancing. By combinations of analysis and simulation, this paper studies the implications of PCFC for how the ABR parameters should be scaled and the advantages of PCFC compared with other existing schemes.**

Index Terms: **ATM, ABR services, parallel communication, traffic control, performance analysis.**

I. INTRODUCTION

ABR (Available Bit Rate) service is expected to efficiently support many important non-real time applications (e.g., LAN emulation, data transfer/retrieval and remote terminal) for which the end systems require a guaranteed QOS. It is able to provide rapid access to unused network bandwidth at up to the peak cell rate, while ensuring low cell loss for the service. It uses a closed-loop feedback control mechanism which dynamically adjusts the allowed cell rates based on the feedback information received from the network. This allows for the sharing of a network link among a number of sources, thus achieving maximum link utilization while maintaining QOS guarantee.

As specified in ATM Forum specification [1], this end-to-end rate control mechanism consists of a Source End System (SES), a Destination End System (DES), a feedback mechanism, and ABR switches. There are two modes of switch behavior although no complete specifications are offered for the switch mechanism: EFCI (Explicit Forward Congestion Indication) and ER (Explicit Rate). The EFCI uses binary rate control, it can only tell the sources whether it should go up or down. As a result, the buffer occupancy oscillates. Also, there exists so-called "beat-down" phenomenon in EFCI environment. An ER switch requires more intelligence, and it provides more information on the supportable rate in the RM (Resource Management) cell to the source, which provides more exact and fair control of the source rate. Thus, the "beat-down" phenomenon can be solved in the ER environment.

All the existing schemes do not change the source characteristics and only allow the VCs to share unused bandwidth in current physical-link. In other words, these VCs can not share the unused bandwidth available on other physical-link even current link congested. Based on the parallel communication [2], a parallel control scheme for ABR services – called *Parallel Communications with Feedback Control (PCFC)*, is proposed in this paper.

The main idea of PCFC is that the information from a source is split into a number of streams, for delivery over separate parallel connections (VCs) which are established according to the QOS requirement and network load during call set-up. The effects of PCFC on the network performance are due to two factors: Traffic splitting and load balancing. In the environment of PCFC, we focus on how to build a control algorithm for accessing the unused bandwidth in whole networks and evaluate the performance of this control mechanism relative to that of traditional scheme.

II. PARALLEL COMMUNICATIONS WITH FEEDBACK CONTROL (PCFC)

In the ATM networks, a VC or VP connection request can be rejected or accepted during call setup. This decision is based on the anticipated traffic characteristics of the VC, the VC's QOS requirements, and the current network load. This procedure becomes more complicated because a set of VCs rather than one are requested in PCFC scheme. The connection request is accepted only when enough network resources are available to satisfy total QOS objectives for both the requesting connection and existing connections. Otherwise the VC connection has to try another route or be divided into smaller one or be rejected. Only if all the VCs of a connection for the parallel request are accepted, can this connection between the source and the destination be established. In addition, the algorithm of bandwidth allocation in a set of parallel connections is another important problem.

A. Algorithm of PCFC

The objective of the rate control mechanism is to ensure that the QOS agreed at connection establishment is obtained at all time, and to allow a connection to use the unused capacity along the path of the connection in the network. The rate control mechanism presented in the ATM-Forum uses network feedback information to adjust and enforce the rate of a connection. The PCFC control scheme we propose establishes a set of parallel connections between the source and destination instead of one connection. Over those connections, the information is coded before sending out. At the receiver, there is no need to re-order

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the sequence of received streams for recovering the original information. In transmission procedure, the scheme would control the transmission rate not only on each VC but also all of the parallel VCs. That is, PCFC adjusts the rate at each VC of the parallel connections in order to satisfy the QoS requirements of the source (e.g., minimum cell rate, loss ration). We use the Explicit Rate mechanism to the PCFC because it has several additional advantages [3], [4], and [5], such as straightforward policing, fast convergence time, and robust against errors or loss of RM cells.

For the PCFC scheme, a set of parallel VCs need to be established between a source and a destination. For each link we consider, multiple VCs from different sources must be considered since they share this link queue. The congestion state is determined by both the queue length and average input rate of all VCs in the link. The source end system adjusts its rate according to ER value in the backward RM cell as pre-agreed at call setup. Also, the source and destination end systems must perform data splitting, coding and reconstruction of information, respectively.

To be compatible with the switch in the ABR environment, we design the source model with parallel scheme to match ER switch as specified in the ATM Forum specification. In the PCFC environment, the following important functions are performed:

Parallel connections set-up—a number of parallel connections between the source and destination are set up in the network using the following bandwidth splitting algorithm: The total bandwidth requirement of B_0 is broken up into a number of fragmented bandwidth requirements B_i, $\sum_i B_i = B_0$, where i is the index of the VCs. If a VC connection with B_i is set up the bandwidth is modified by:

$$B_0 = B_0 - B_i \tag{1}$$

to correspond to the remaining bandwidth requirement. This remaining bandwidth, $B_0 - B_i$, is used to find the next connection on other separate paths (e.g., link or port) in the network. This procedure is repeated until the remaining bandwidth reaches zero. Then a set of parallel connections with total bandwidth as the source requested are set-up.

An alternative is to divide the MCR by m and then try to find m parallel connections in the network. If any one of the connection can not be set up, the overall connection is rejected.

Other functions in the switch, such as, early congestion detection based on a positive derivative of the queue length, load monitoring, exponential weighted averaging, bandwidth reallocation, and ER calculation are performed similar to that in EPRCA (Enhanced Proportional Rate-Control Algorithm) [4], [6], and [7] scheme.

B. Operation of PCFC

For the ABR data cells, a set of parallel connections are set up according to the procedure described above. Once the parallel connections as requested are established, the source begins cell transmission. The value of MCR is determined during parallel call setup, or it is simply divided by the number of parallel connections MCR/m. The PCR may also be divided by m equally, however, to increase the throughput and network utilization on the link with light traffic load, we may enlarge the PCR value on each VC, $\gamma PCR_i/m$, $\gamma > 1$ called *PCR splitting factor*. This procedure makes the connection between the source and destination easy to set up. Transmission of data cells is preceded by sending of RM cell. The RM cell is processed like traditional ABR services except by each VC separately.

It should be noted that, in the PCFC, the source will also adjust the total transmission rate among the parallel VCs based on the queue length in a buffer at the source end and returned RM cells. In other words, the source may allocate the bandwidth among the parallel VCs to transmit data cells in order to achieve high throughput.

The operation behavior of the source, destination and switching is described as the following

Source End System Behavior: For PCFC scheme, the source behavior is quite different from the case of traditional ABR sources. During call set-up, the source splits the bandwidth requirement into a number of, such as m, smaller ones and tries to set up m parallel connections in the network, this is based on (1). The source starts sending cells at an initial cell rate (ICR). For every $N_{rm} - 1$ data cells sent, an RM cell is generated by the source. During the sending of data cells, it dynamically adjusts the cell rate for each VC according to all feedback RM cells from the group of parallel connections (VCs) instead of one feedback RM cell of these VCs. In other words, the rates of the group VCs are co-adjustment under the agreement of PCR and MCR.

Destination End System Behavior: The destination behavior is similar to tradition one except for buffering arrived data cells and reconstructing the original information after all data cells are received from the parallel connections.

Switch Behavior: The switches are of not only the functions of ABR service required but also the functions of parallel scheme required such as parallel routing. When a forward RM cell arrives, the switch calculates a Mean Allowed Cell Rate (MACR) by using the exponential weighted averaging:

$$MACR = (1 - \alpha) * MACR + \alpha * ACR, \tag{2}$$

where $\alpha = AVF$ is averaging factor. The switch also monitors the load factor(LF = input-rate/link-rate) every N data cells. If $LF < 1$ and there is no congestion in it, the MACR is increased by

$$MACR = MACR + \Delta, \tag{3}$$

where $\Delta = MAIR$ is the increment of leftover bandwidth reallocation (e.g., $\Delta = 0.5$Mbps). Otherwise, in the overload state ($LF > 1$), it reduces the MACR by a factor of MRF (MACR Reduction Factor, e.g., 0.95) $MACR = MRF * MACR$, and modifies the ER field and CI state of backward RM cells if necessary.

III. SCALING OF PARAMETERS AND ANALYSIS

The PCFC control scheme we have described can be modeled by queueing systems with delayed feedback where the service times and job arrivals are time-varying and state-dependent. The analysis of such systems, however, is known to be extremely difficulty; only simple models have been considered in the literature [5], [8], [9], and [10]. In this paper, we shall make no attempt to give a complete rigorous analysis of the scheme. Instead, we shall derive analytical results for a simple network model.

In the following analysis, we consider N sources with identical parameters. RTT is the round trip delay between the source and destination. We first investigate the effect of PCFC on ABR parameters and discuss the stability of the PCFC mechanism. Then we devise a simple analytical model to estimate the buffer occupancy in the equilibrium and transient states. We also discuss the smoothness and delay time of the PCFC mechanism.

A. Parameters Adjustment

The PCFC control scheme is achieved by a series of algorithms in switches and end systems as described in Section II, such as the calculation of ER based on (2) and (3). When switches are both under-loaded and there is no congestion, combining (2) and (3), the MACR is calculated and updated when a forward RM cell is received:

$$MACR = (1-\alpha)\cdot MACR + \alpha \cdot ACR + \Delta. \qquad (4)$$

The values suggested in ATM Forum are $\alpha = 1/16$ and $\Delta = 0.5 Mbps$. In the PCFC scheme, the traffic from the ABR source is split into m sub-sources with lower values of MCR and PCR. We now investigate the effect of PCFC on scaling of these ABR parameters.

Bandwidth increment – Δ: The bandwidth increment is used to re-allocate the unused bandwidth for VCs in the link. Larger values of Δ will make MACR increase faster, and the connections will acquire the excess bandwidth more quickly. On the other hand, when the network reaches the equilibrium state, too large a value of Δ may cause the rate and queue occupancy to oscillate widely. Therefore, the bandwidth increment must be chosen appropriately. In the traditional ABR environment, it is suggested that $\Delta = 0.5\ Mbps$. In the PCFC mechanism, if the increment step is set at a low level, $\Delta' = \Delta/m$, the increment rate for one sub-stream is factored by $1/m^2$ rather than $1/m$. This is because the cell rate in one connection is $1/m$ times that of the non-parallel case, and the RM-cell interval is correspondingly m times that of the non-parallel case. To obtain an increment rate $1/m$ times that of the non-parallel case, it is therefore necessary that $\Delta' = \Delta$.

Averaging factor – α: This parameter determines how fast the MACR converges to mean ACR. The value of α should be kept the same, i.e., $\alpha = 1/16$, since there is no reason why the convergence rate in the parallel case should be different from that in the non-parallel case.

RM-cell interval – T_{rm}: As discussed before, the cell rate is reduced to a lower value in the PCFC mechanism, and the RM-cell interval is extended correspondingly.

B. Stability

When a switch receives an RM cell, it updates MACR(t) by (2) or (3). In the following, we study the stability of the ABR control scheme (both traditional and PCFC schemes) and present our findings.

Denote $MACR(t)$ by $y(k)$, $ACR(t)$ by $ACR(k)$, and MAIR by Δ, where k is the index of the RM cells being received at the switch. Assuming the initial value of MACR is $y(0) = y_0$ and $y(1) = y_1$, the $ACR(t)$ is feed-backed from $MACR(t-2)$ (i.e., delay of two RM cell intervals), denoted by $ACR(k) = y(k-2)$. We assume the case of no congestion in the network and all cell rates of the connections are controlled by the switch; that is, the sources can send cells at the rate of ACR to the network. Representing the calculation of MACR as

$$\begin{aligned} y(k) &= y(k-1) + \alpha[ACR(k) - y(k-1)] + \Delta \\ &= y(k-1) + \alpha[y(k-2) - y(k-1)] + \Delta \qquad (5) \end{aligned}$$

where $k = 2, 3, 4, \cdots$. This is a difference equation. Given known input Δ and known values of $y(0) = y_0, y(1) = y_1, y(k)$ can be determined for all k. With some tedious computations and deduction, we can find the general term of MACR after the reception of k RM cells at the switch as:

$$\begin{aligned} y(k) &= y_1 + \frac{\alpha}{1+\alpha}\left[y_0 - y_1 + \frac{\Delta}{1+\alpha}\right][1-(-\alpha)^{k-1}] \\ &\quad + \frac{\Delta}{1+\alpha}(k-1), \qquad k = 2, 3, 4, \cdots. \qquad (6) \end{aligned}$$

Equation (6) indicates that the value of MACR depends on the initial rates y_0, y_1 and the rate increment Δ. Given $\Delta > 0$, the value of MACR increases as the number of updates k increases (i.e., $\lim_{k\to\infty} y(k) = \infty$), so that the bandwidth or buffer space can be allocated for the connections until the user's PCR is reached or the network is congested. From the stability point of view, this "unstable" situation is desirable for increase of ACR. In addition, the parameters of Δ and α determine how fast the MACR will reach a certain rate (e.g., PCR, or link capacity). The larger the increment, the faster the MACR and ACR increase. However, larger values of the increment means larger rate adjustment, and this may result in rate and buffer occupancy oscillations when the network reaches an equilibrium state.

As described before, the source may not be able to send cells as fast as ACR allows (called limited ABR source) due to application or end-system architectural constraints (such as contention for access to a disk or a local scheduler congestion, or simply the source does not need the high rate). The switch would allocate the leftover bandwidth to other sources which have larger PCR value and need more bandwidth, and also that are not congested in other switches.

There are two connections in the switch $SW2$ we shall consider, as shown in Fig. 1. The cell rate of connection 1 is constrained at $v \ll c$ (c is the link bandwidth) by the switch $SW1$ in its path rather than the switch $SW2$ of focus. The peak cell rate of the source $source2$ is nv ($n > 1$ is an integer). Let us now investigate the changes of ACR.

To simplify analysis, we assume that the rate of RM-cell sent by the ABR source $source1$ is $1/n$ times that of the other source. The ACR value of RM-cell sent the $source1$ is set to its constrained value v. For the other source, this value is set

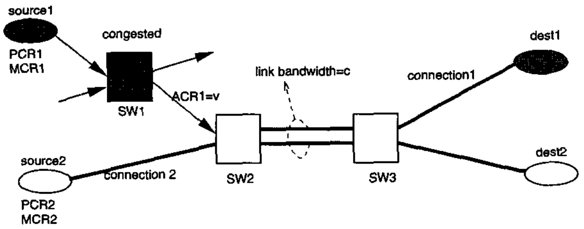

Fig. 1. One of the connection is constrained at a low cell rate ($ACR_1 = v$).

according to computed $MACR$. That is

$$ACR(k) = \begin{cases} v, & \text{for } k = jn, (j = 1, 2, \cdots) \\ y(k-2), & \text{otherwise} \end{cases} \qquad (7)$$

Let us first find the $y(k)$ for $k = 2$ to $n+1$, then for $k = n+l$ ($l = 2, 3, \cdots, n+1$), and then derive the general term of $y(k)$ for $k = jn + l$, ($j = 0, 1, 2, \cdots$).

The term of $y(k)$ for $k = 2$ to $n+1$ can be determined by (6). By means of iteration, the general term is given by

$$\begin{aligned} y(jn+l) = \; & y(n+1)A(n+1)^{j-1} \cdot A(l) \\ & + B(n+1)\tfrac{1-A(n+1)^{j-2}}{1+\alpha} \cdot A(l) + B(l) \end{aligned} \qquad (8)$$

where $A(l) = \frac{1-(-\alpha)^l}{1+\alpha}$, $B(l) = \frac{\Delta(l-1)}{1+\alpha} + \frac{\Delta + v(1+\alpha)}{(1+\alpha)^2}\alpha[1-(-\alpha)^{l-1}]$, $y(n+1)$ can be calculated from (6) and $j = 0, 1, 2, \cdots, l = 2, cdots, n+1$. To observe the boundary of the equation, we set the l to the maximum value of j period, $l = n+1$, then for small α (e.g., $\alpha = 1/16$) we have

$$\begin{aligned} \lim_{j \to \infty} y(jn+n+1) &= n\frac{\Delta}{\alpha}\frac{1}{1-(-\alpha)^n} + \frac{\Delta}{1+\alpha} + v \\ &\approx n\frac{\Delta}{\alpha} + \frac{\Delta}{1+\alpha} + v. \end{aligned} \qquad (9)$$

Equation (9) indicates that the MACR of the ABR control (both traditional and PCFC) scheme is bounded when some of the connections in a link are congested by other switches or constrained by sources. This boundary is a function of parameters α, Δ and congested ACR value v. To use the link bandwidth efficiently, this boundary must be greater than the PCRs of the uncongested sources (e.g., PCR_2 of *source2*) or greater than the link bandwidth c. In other words, the parameters should satisfy:

$$\lim_{j \to \infty} y(jn+l) \geq \max\{PCR_i, c\}$$

$$\Delta \geq \frac{[max\{PCR_i, c\} - v]\alpha}{n}, \quad \text{for } (\alpha \ll 1), \qquad (10)$$

where PCR_i is the PCRs of the uncongested sources in the link. Like the traditional ABR scheme, PCFC can not solve this problem completely. However, it makes (10) easier to be satisfied due to traffic splitting and parallel routing. This issue of ACR boundary remains to be further studied.

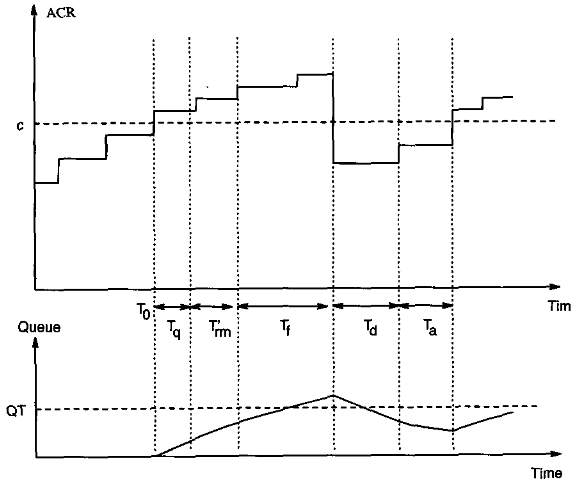

Fig. 2. Allowed cell rate and queue length in the equilibrium state.

C. Buffer Occupancy

Cell loss due to RM cell delays can be reduced by reserving sufficient buffer memory in excess of a congestion threshold. To limit the cells sent by a start up VC during the first RTT, and also to protect the network in case of destination failure, a limit (Xrm) on the number of RM cells which may be sent before any RM cell being received is defined. After Xrm RM cells have been sent the source must decrease its rate in each RM cycle. To estimate the buffer occupancy, we model the additive and multiplicative decrease by using the differential equation approach of [11].

Recall that the rate increase and decrease algorithm in the source behavior are:

$$ACR(t) = ACR(t_0) + a \quad \text{if no congestion} \qquad (11)$$

$$ACR(t) = d \cdot ACR(t_0) \quad \text{if congestion,} \qquad (12)$$

where t is the current time and t_0 is the time of the last rate change, $\alpha = 1/16$, $a = 0.5$Mbps is the ACR additive increase rate (AIR), and $d = 0.95$ is the ACR reduction factor (RDF). Note that the time interval $t - t_0$, strictly speaking, is not fixed during rate adjustment. It has a long period when the current cell rate (CCR) is low, and vice verse. In the analysis, we consider the feedback delays for all connections are the same. The object of the analysis is to investigate whether the PCFC mechanism is superior in terms of buffer occupancy compared with the non-parallel scheme with feedback control.

At Equilibrium State

First, we consider the rate and queue processes in an equilibrium state, as shown in Fig. 2, during which the arrival rate at the link fluctuates around the link bandwidth and there is no new active connections added or existing ones removed. Also, the use-it-or-lose-it policy is adopted when the active source is idle for a long period. At time T_0, the rate exceeds the link bandwidth c, and the queue starts to build-up. At time $T_0 + T_q$, the positive queue derivative is detected by the switch–with the so-called early congestion detection; it would cause the switch to enter a congestion state. The ER value computed by the switch and state of CI = 1 are filled in next backward RM-cell. After a period of delay, T_f, which is the round-trip time between the source and the switch. The RM cell reaches the source, the ACR is decreased, and cells with the new ACR arrive to the switch. The queue length reaches a peak as the rate drops back to the link bandwidth. During time T_d and T_a the load factor $LF < 1$, ACR is increased by (11) again.

Let R_{max} be the maximum rate and Q_{max} be the maximum queue length. We have

$$R_{max} = c + a \cdot N' \cdot \lceil \frac{T_q + T'_{rm} + T_f}{T'_{rm}} \rceil, \tag{13}$$

where T'_{rm} is the interval of two RM cells for each connection, and $N' \cdot \lceil \frac{T_q + T'_{rm} + T_f}{T'_{rm}} \rceil^2$ is the total number of RM cells received at $N' = mN$ parallel ABR sources during the period of the rate over the link bandwidth, $T_q + T'_{rm} + T_f$, at the switch. For the worst case, consider the switch closest to the destination. The value of $T_f \approx RTT$, and the bound on the maximum queue length in the equilibrium state can be easily obtained as

$$\begin{aligned} Q_{max} \quad & \leq \int_0^{T_q + T'_{rm} + RTT} (R_{max} - c) dt \\ = \quad & aN'(T_q + T'_{rm} + RTT) \lceil \tfrac{T_q + T'_{rm} + RTT}{T'_{rm}} \rceil. \end{aligned} \tag{14}$$

Equation (14) indicates that the maximum queue length accumulated in the equilibrium state depends on the round trip time and the time of the congestion condition measured, as well as the rate increment of each step, a. It increases linearly with the increase in a but not linearly with RTT.

The number of VCs N' increases m times due to the bandwidth splitting in the PCFC. On the other hand, the average rate of each VC is decreased by the same scale. Thus, the time period of T'_{rm} in each sub-source is expanded m times, and the total number of RM cells received from N' sources, $N' \cdot \lceil \frac{T_q + T'_{rm} + RTT}{T'_{rm}} \rceil$, is approximately the same, resulting in the same buffer occupancy compared with the non-parallel case.

In short, the PCFC control scheme will not increase the maximum queue length in the equilibrium state due to source splitting.

At Transient State

When a new connection request is accepted to a link and it begins to send cells, the existing active connections on the link with rate exceeding their MCR values may be required to reduce their rate. After a rate transition period, the rates of the new and existing active connections will reach another equilibrium state with each having a rate relative to its MCR, PCR and MACR. During the period of the transient state, the queue length will increase even over the threshold. On the other hand, when an active connection is released. The queue may become empty during a period of rate adjustment of other connections. This problem relative to the network utilization is not studied in this paper. Here, we consider the buffer occupancy of PCFC in the transient state.

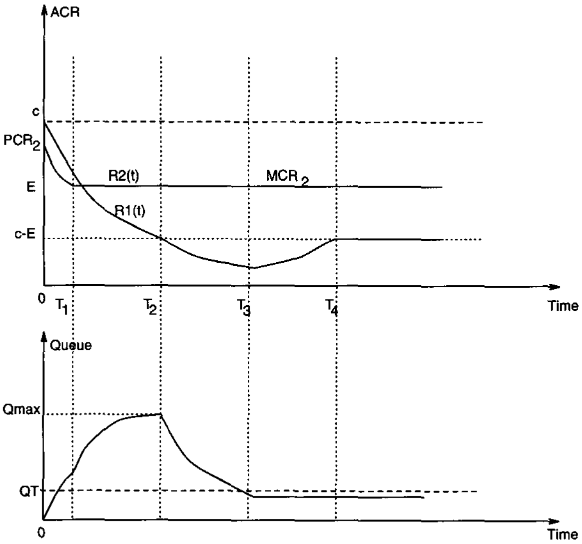

Fig. 3. Rate and queue changes in the transient state.

During the rate transition in the transient state, the aggregate arrival rate at the queue may significantly exceed the link bandwidth and create a queue build-up. If the sum of the MCRs of the existing active connections is close to zero and the MCR of a newly active connection is close to the link bandwidth, the aggregate arrival rate at the link can be as high as twice the link bandwidth. In this case, a significant queue backlog is accumulated. Although the newly connection can be split into m subconnections with small MCR and PCR in the PCFC scheme, we are interested in the worst case (i.e., MCR close to the link bandwidth) queue build-up in the transient state, and we use this queue build-up as an estimate of the buffer occupancy. Let us consider the following worst case. We assume that the sum of the MCRs of the existing active connections is equal to 0 and the newly active connection has an MCR equal to E ($c/2 \leq E < c$). We denote by $R_1(t)$ the aggregate rate of the existing active connections at time t. Let $t = 0$ be the time instance when the cell of the newly active connection first arrives at the link. We assume that the existing active connections use the entire bandwidth at $t = 0$, $R_1(0) = c$. We denote $R_2(t)$ as the rate of the newly active connection with initial rate, ICR, set to PCR so that $R_2(0) = PCR_2 = B$ ($E \leq B \leq c$).

In the analysis, we ignore the rate fluctuations in the equilibrium state. Thus, we have $R_1(0) = c$, $R_2(\infty) = E$. The rate and queue fluctuations in the equilibrium state are relatively "high-frequency" changes and smaller in magnitude compared with those in the transient state. We illustrate the rate transition and queue build-up in Fig. 3, where, $R_2(t)$ reduces to its MCR E at time T_1, and $R_1(t)$ reduce to $(c - E)$ at time T_2, $T_1 \leq T_2$ as $E < c/2$ and $E \leq B \leq c$. When the aggregate rate of $R_1(t)$ and $R_2(t)$ is greater than the link bandwidth c, the switch becomes congested and the queue length starts increasing (during 0 to T_2). The RM cells carries this information to the sources. The sources then reduce their allowed cell rates until the switch is non-congested at T_3. Although the aggregate rate of $R_1(t) + R_2(t)$ is lower than the link bandwidth at time T_2

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[2] Let $\lceil x \rceil$ denote the minimum integer greater than or equal to x.

to T_3, the $R_1(t)$ is reduced continuously since the queue length exceeds the queue threshold QT and $R_2(t)$ has reached MCR_2.

According to the operation algorithm at the source end, the rates of the two connections in the transient state are

$$R_1(t_0 + \Delta t) = d \cdot R_1(t_0), \qquad 0 \leq t_0 \leq T_2 \tag{15}$$

$$R_2(t_0 + \Delta t) = \begin{cases} d \cdot R_2(t_0), & 0 \leq t_0 \leq T_1 \\ E, & t_0 \geq T_1, \end{cases} \tag{16}$$

where t_0 is the time of the rate last adjustment, and Δt is the time interval of RM-cells, it is proportional to the current cell rate: $\Delta t = N_{rm}/R(t_0)$. Denote by n_1 the number of adjustments for $R_1(t)$ from c to $c - E$ (i.e., number of RM-cells received by the source from network during time (0, T_2)). Let n_2 be the number of adjustments for $R_2(t)$ from $PCR_2 = B$ to $MCR_2 = E$. Then n_1 and n_2 can be obtained from

$$R_1(T_2) = d^{n_1} R_1(0) = c - E$$

$$R_2(T_1) = d^{n_2} R_2(0) = E$$

as $n_1 = \lceil \ln \dfrac{c-E}{c} / \ln d \rceil, n_2 = \lceil \ln \dfrac{E}{B} / \ln d \rceil$. Since the time period of rate adjustment $(\Delta t)_i$ is proportional to the current cell rate, by (15) and (16), we have:

$$T_1 = (\Delta t)_1 + (\Delta t)_2 + \ldots + (\Delta t)_{n_2} = \frac{N_{rm}}{B} \cdot \frac{d(B-E)}{E(1-d)}$$

$$T_2 = \frac{N_{rm}}{R_1(0)} \cdot \frac{d^{n_1} - 1}{d^{n_1} - d^{n_1 - 1}} = \frac{N_{rm}}{c} \cdot \frac{dE}{(c-E)(1-d)}.$$

Therefore, the queue build-up in transient state $(0, T_2)$ is the difference of the number of entering and leaving cells, denoted by Q_{max}, is:

$$\begin{aligned} Q_{max} = {} & n_1 \cdot N_{rm} + n_2 \cdot N_{rm} + E(T_2 - T_1) - cT_2 \\ = {} & \tfrac{N_{rm}}{\ln d} \ln \tfrac{(c-E)E}{cB} - \tfrac{EN_{rm}d}{1-d} \left[\tfrac{1}{c} + \tfrac{B-E}{BE} \right]. \end{aligned} \tag{17}$$

We plot the buffer occupancy in terms of MCR_2 (PCR_2) and a number of rate adjustments in Fig. 4. It is shown that the maximum queue size decreases as the MCR or PCR is reduced, as expected. For a given MCR, the lower the PCR, the smaller the buffer occupancy.

From the network point of view, a newly active connection should have a "slow start" (i.e., small value of PCR_2), to avoid a large queue build-up at the transient state. How the queue changes in terms of the number of rate adjustment is depicted in Fig. 4. When PCR is given, the smaller MCR corresponds to smaller buffer queue, as shown in break line with $PCR_2 = 150, MCR_2 = 100, 120, 140$ in Fig. 4.

Since the MCRs and PCRs are split into smaller value (i.e., rate splitting), the buffer occupancy of switches can be reduced by PCFC mechanism.

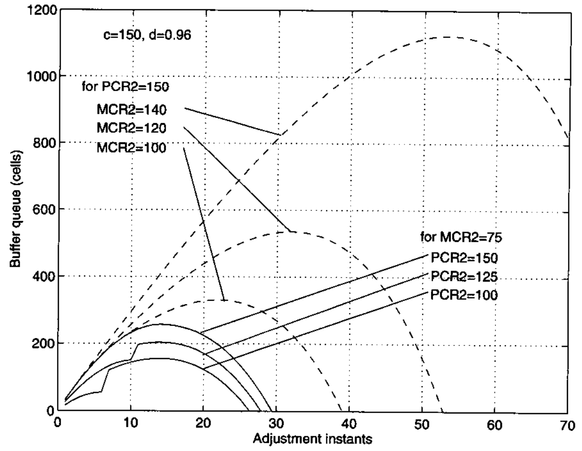


Fig. 4. Buffer queue vs. rate adjustment instants in the transient state with $c = 150 Mbps, d = 0.95$.

D. Rate Fluctuation

The smoothness is defined as the ratio of the amplitude of oscillation of the allowed cell rate to the total rate of cell transmitted by source. For the purpose of comparison, we assume that the MCR of original traffic is equally split into $MCR' = MCR/m$, and the ACR is reduced to ACR/m. Then the $MACR'$ in the PCFC is given by:

$$MACR' = (1 - \alpha) MACR' + \frac{1}{m} \alpha ACR. \tag{18}$$

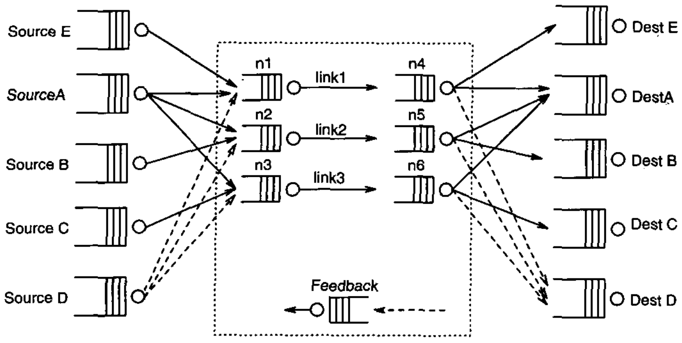
Equation (18) indicates that the mean ACR of PCFC, $MACR'$, is smaller than that of the non-parallel communications due to the factor $1/m$. Thus, the amplitude of oscillation of rate adjustment depending upon the second term in (18) is reduced due by the factor $1/m$. Therefore, the equally fair-share bandwidth of PCFC, and furthermore, the ACR adjustment, changes in a smoother way than that in traditional ABR environment.

When the MCR and CCR are not equally split, says MCR'_i and ACR'_i, $(1 < i < M$, M is total number of splitting connections on the link), by the PCFC scheme, similar results can also be obtained.

E. Average Delay Time

The strict analysis of the delay time of a cell or packet in the PCFC environment is not simple. For the purpose of comparison, we present an intuitive but simplifying argument to show which one is better in terms of average delay time between the PCFC scheme and traditional ABR scheme (no-parallel with feedback control).

We consider a communication network, which consists of m separate channels and serves N independent sources each with rate λ. For the traditional ABR scheme, one channel with separate feedback control is assigned to one traffic stream, and the bandwidth and buffer space can only be used by one source traffic. Bursty traffic will build up a large amount of queueing and therefore will suffer large delay even though other channels may be idle at that time. Thus, the delay time of a cell through the channel is highly affected by the traffic burstiness. In the case of the parallel communication scheme—PCFC environment, each



Source A: parallel ABR source (split: ABRa1,ABRa2, ABRa3)
Source B,C,E: non-parallel ABR sources
Source D: on-off source

Fig. 5. Simulation model with feedback control for ABR services.

source is split into m sub-streams, and then delivered over the m parallel paths (links); the traffic load is balanced and smoothed on the network links. This can be regarded as a system in which the N sources share the resources of the m links (their bandwidths and buffer space) to transmit data cells. The delay time on the link can be reduced due to the following reasons: (1) The sub-streams are routed to paths based on minimum queueing length and feedback control scheme. It balances the traffic load on each link, i.e., each path has an approximately equal queue length. The end-to-end average cell delay time on each path is approximately the same; (2) The N sources share the network resources with each other and the traffic is statistically multiplexed over the links, the traffic load is smoother and the link resources are used more efficiently. Therefore, the queue length and average delay time with the PCFC mechanism are smaller than that in the traditional ABR environment.

It is necessary to point out that, in the analysis of this section, we assume that the round trip delay time (RTT) of RM cell is approximately fixed (RM cell has higher priority than data cell). When the variation of RTT is considered, the performance analysis can be very complicated. In addition, for strict network utilization, we should take into account the packet overhead due to splitting.

From the call admission control point of view, the connection can be more easily established than that in the traditional ABR system when network loads are heavy, i.e., the probability of connection-rejection at call-setup can be reduced. The reason is that m channels of small bandwidths can be grouped for a parallel source. It will lower the blocking probability for call admission control, as a big junk of bandwidth does not have to be found on the same link.

IV. SIMULATION INVESTIGATION ON RESULTS

There have been many interesting papers [3], [7] that use the simulation method to study the performance of the ABR service in the traditional non-parallel setting. In this section, we shall use simulation to investigate the buffer occupancy and smoothness of allowed cell rate in the PCFC environment. Four types of traffic sources, the parallel ABR source, non-parallel ABR sources, CBR source and bursty traffic (on-off source) without feedback flow control, are considered.

Table 1. Some of PCFC parameters used in simulations.

Parameters	Default Value	Description
PacketSize	424 bit	cell size
LinkRate	155.52 Mbps	link rate
L_{us}	10 Km	user to switch
L_{ss}	50 Km	switch to switch
BufferSize	500 cells/port	buffer size
Q_h	100 cells	congestion TH
Q_l	50 cells	uncongested TH
N_rm	32 cells	RM cell period
RDF	0.95	
MAIR	0.5 Mbps	
AIR	0.5 Mbps	
AVF(α)	1/16	
MRF	0.95	
N_{count}	100	Measurement interval
Source A: PCRa=150; MCRa=90; ICRa=120; Split sources (ABRa1,ABRa2,ABRa3): PCR=60; MCR=30; ICR=40;		
Source B,C,E:ABRb,ABRc,ABRe PCR=70; MCR=30; ICR=60;		
Source D: On-Off VBR Source: onBitRate=30; onAvgPkt=2000; onProb=0.85;		
CBR Source: BitRate=50;		

A. Model Description

Fig. 5 shows the network model used in our simulation. This model consists of three types of elements – the sources, network elements, and destinations.

Characteristics of the Sources— The types of sources used in this work are listed and described below:

An ABR source that employs parallel routing (Source A) – The data cells are generated by a CBR source model and are buffered in a buffer of infinite size at the source. This is a greedy source that pumps as much data into the network as is allowed. Since there is no cell loss in the ABR environment, we only consider the situation of no coding in the PCFC scheme (i.e., $k = m$). The parallel ABR Source A is split into ($m = 3$), ABRa1, ABRa2 and ABRa3, and then transmitted over the parallel VCs which are set up according to the previous procedure. To adjust the send rate on each VC, a buffer for each VC is needed in the source end before the cell goes into the network. The source determines where the next cell goes —based on the minimum queue in the buffers. The transmission rate allowed on each VC (ACRa1,ACRa2 and ACRa3) is controlled by the RM cell received from networks. After splitting, each sub-stream has smaller MCR and PCR values than the pre-split stream.

Three ABR sources do not employ parallel routing (Source B, Source C and Source E) – These are the traditional ABR sources.

A VBR bursty source (Source D) — There is one VBR source. It is an on-off source. The data cells enter the network immediately after they are generated, and each burst of cell arrival of the source is randomly destined for any one of the three switches ($n1, n2, n3$) in Fig. 5.

Network Control Mechanism— As shown in Fig. 5, the network we model consists of six ER switches ($n1 \sim n6$) in two stages. The end-to-end distance is about 70 km. The function and control algorithms of the switches have been described in Section II. In addition to switching traffic, a switch must also perform the load monitoring, ER computing, congestion detection, and modification of the information in RM cells for feedback purposes. It should process the forward and backward RM cells quickly.

Destinations— DestA, DestB, DestC, and DestE are the destinations of SourceA, SourceB, SourceC, and SourceE, respectively. DestD collects all data cells sent by the VBR source.

Table 1 shows the specific parameter values used in a particular experiment that we ran.

B. Experiment Results

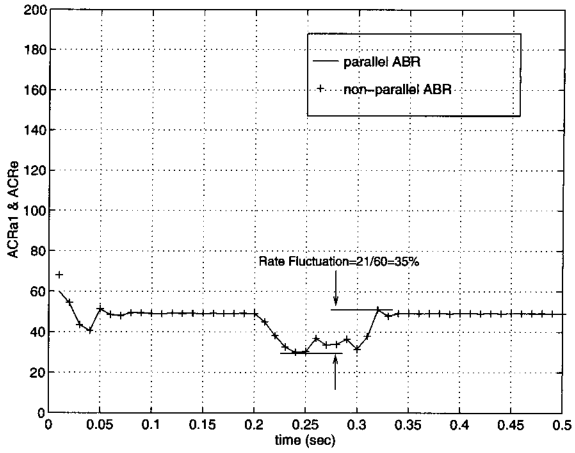
Fig. 6 and Fig. 7 show a set of simulation results based on the PCFC model. The data value in these figures are collected and averaged over a simulation period of 10ms.

Smoothness of ACR

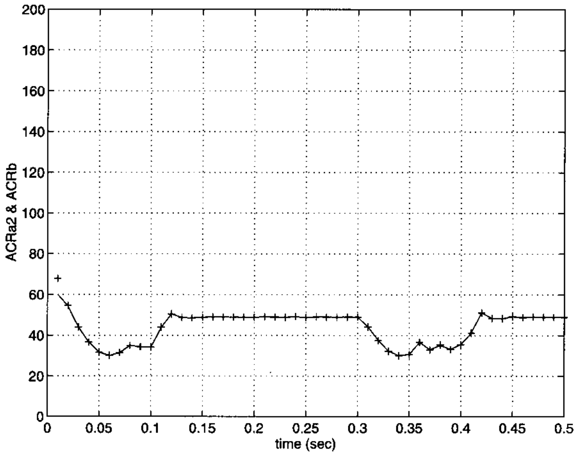
To estimate the smoothness of the allowed cell rate for parallel ABR sources, we simulate the model shown in Fig. 5, the parameters are listed in Table 1. One on-off source transmits the data cells of each burst arrival randomly to one of the three connections (switches) when it is on. This forces the allowed cell rate of each VC on the connection to be reduced, as shown in Fig. 6 (a) and (b).

The solid line indicates the rate of the parallel source in the connection, the line of "+" presents the rate of non-parallel sources. Although the ACRs on an individual connection is reduced during the active period of the on-off source that connection, the parallel ABR source with PCFC mechanism may share other bandwidths of connections in which on-off source is idle at this time. Thus, the total allowed cell rate of the parallel source is lowered by a smaller amount. By the definition of the smoothness in Section III, the allowed cell rate of the parallel ABR sources is smoother than that of traditional ABR sources. Comparing the rate fluctuation of non-parallel ABR Source ABR_e and parallel ABR source ABR_1 in Fig. 6 (a) and (c), we can see that the rate fluctuation (13.6%) of parallel source is smaller than that of traditional ABR source (35%).

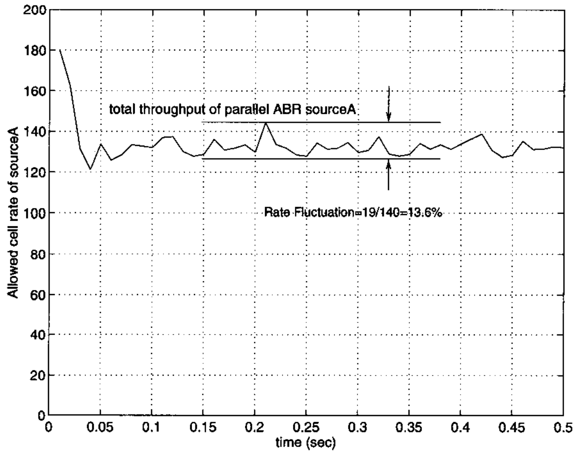
It should be noted that, if the rates parameters (e.g., PCR, MCR) of two ABR sources differ by a large amount, the bandwidth may be allocated unequally in relation to their requirements. The source with the requirement of low rate may be allocated more bandwidth. This is because of the algorithm on bandwidth allocation among VCs based on the exponential weighted averaging. In general, the parallel source with splitting may take on more bandwidth (i.e., high QOS) than that of no splitting source as long as the rates after splitting are smaller than the MACR of the link. In the case of all parallel ABR sources with smaller MCRs,PCRs and ICRs, the traffic in links are smoother and balanced. Furthermore, we can say that choosing the appropriate parameters of source splitting, the total transmission rate of the parallel ABR source may guarantee not only a higher ACR level but the traffic will also be smoother. Therefore, the ABR source with PCFC mechanism can be allocated more bandwidth or may have smoother allowed cell rate.



(a) Allowed cell rate on link 1.



(b) Allowed cell rate on link 2.

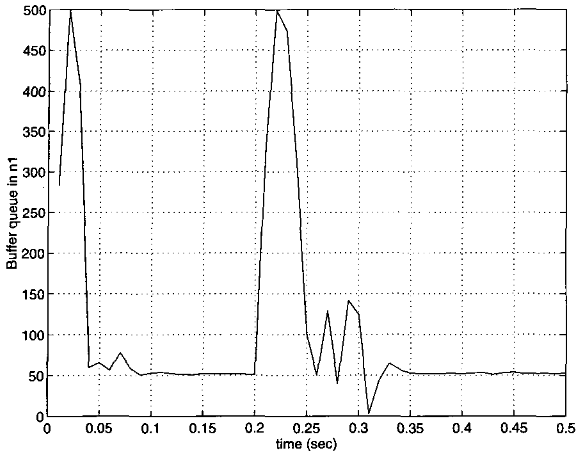


(c) Total allowed cell rate of parallel ABR SourceA.

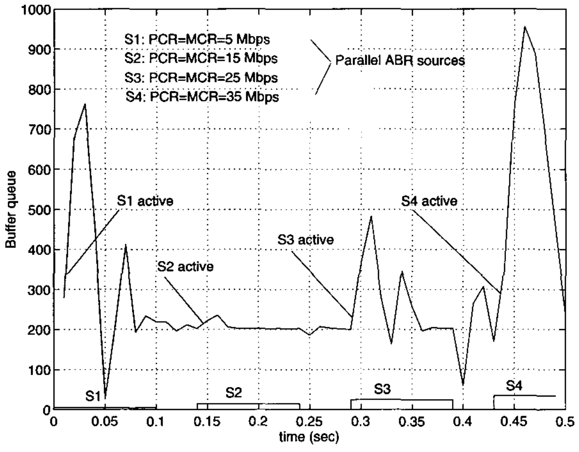
Fig. 6. Comparison of ACR smoothness for parallel and non-parallel ABR sources.

Buffer Occupancy

When the on-off source is active in the link during an equilibrium, the instant input rate to the link may exceed the link band-



(a) Buffer queue with ABR and on-off source (QT=50 cells).



(b) Buffer queue with newly connection active (QT=200 cells).

Fig. 7. Buffer queue in link 2 with parallel and non-parallel ABR sources (buffer size=1000 cells, S4-traditional ABR source).

width and causes the average queue length to grow beyond the threshold. Upon receiving network feedback information, the ABR sources relative to the congested link reduce their allowed cell rate. It increases the rate again after the queue length drops below the threshold. The buffer queue changes dramatically as the an on-off source becomes active and idle. At the equilibrium state, the buffer queue changes around the queue threshold. Fig. 7 (a) depicts this situation (queue threshold $QT = 50$ cells) with buffer size 1000 cells and PCR=MCR=25 Mbps as the source on.

Fig. 7 (b) illustrates the changes of queue in $link2$ in the case of newly parallel ABR sources $S1, S2, S3$ and non parallel ABR source $S4$ active. At the beginning, the input rate of the existing ABR sources exceeds the link bandwidth, and the buffer queue grows. After the transient state (time 0.1 sec), the queue reaches $QT = 200$ cells. At time 0.14 sec, source $S2$ with worst case of MCR=PCR=15Mbps is active ($S1$ idle), the queue grows a little bit and reaches equilibrium state very quickly. When new source $S3$ with PCR=MCR=25Mbps is active, the instant rate exceeds link bandwidth by a large amount, and the buffer queue grows a large scale. When the traditional ABR source $S4$ with higher MCR and PCR becomes active at time 0.43sec., the buffer queue grows to a lare value. Therefore, the lower the rate of newly connections, the lighter the effects of it on the buffer queue. The parallel ABR source with low PCR/MCR can reduce the buffer occupancy due to traffic splitting and smoothing.

The analysis and simulation results show advantages of PCFC scheme. The issues of its complexity and management of the multi-connection call set-up and ABR parameters should be paid more attention in particular. This is eliminated due to space limitation of this paper.

V. CONCLUSIONS

This paper has described a parallel communications with feedback control (PCFC) mechanism for ATM networks. It is studied and investigated by means of a combination of analysis and simulation. The results show that the sources using PCFC scheme may equally share and highly utilize the available bandwidth over the whole network instead of over the one physical link mentioned in the traditional ABR environment. Furthermore, the buffer occupancy and delay time can be reduced by the PCFC mechanism; the connection between a source and destination can be established more easily due to traffic splitting; and the parallel ABR sources can be served with a higher quality of service (i.e., high throughput and small rate variation) from a group of sub-connections compared to those of the traditional ABR service.

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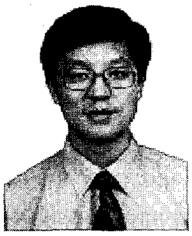

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