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Integration of Pricing and Flow Control for Available Bit Rate Services in ATM Networks*

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ABSTRACT We present a theoretically justified pricing scheme for ABR services which utilizes mechanisms provided by rate-based flow control as defined by the ATM Forum. As a result, the scheme imposes no additional communication overhead, while the added complexity at the switches and end-systems is minimal. Our approach complements ABR's rate-based flow control and leads to economically efficient utilization of network resources. According to the scheme, a connection is charged based on the sum of the price per unit of bandwidth on all links along its route. Prices depend on the demand for bandwidth and are adjusted in a decentralized and iterative manner. Simulation results show that prices converge reasonably fast and do not have a negative effect on the convergence properties of flow control.

1 Introduction

The Available Bit Rate (ABR) service class is one of the five service classes identified by the ATM Forum for ATM-based integrated services networks, [1, 2]. It is intended for "best-effort" traffic which impose no bounds on delay or delay variance[1]. By considering the tremendous and unprecedented growth of the Internet which - currently - supports only a best-effort service model, it is easy to see that such traffic will constitute a significant portion of the traffic carried by integrated services networks. This suggests the need of a theoretically justifiable, yet efficient scheme for pricing ABR services.

Pricing best-effort services in addition to guaranteed services is discussed in [3]. In the proposed scheme, best-effort services are charged according to their average cell rate. As in our approach, prices depend on demand and can be iteratively adjusted. In [11], a per-cell spot pricing scheme is proposed. Employed in conjunction with a guaranteed services pricing model, the scheme is shown to lead to optimal pricing. In [9], a feedback pricing scheme which treats Constant Bit Rate (CBR), Variable Bit Rate (VBR), and ABR requests for bandwidth identically is described. Prices depend on the network load (tending to infinity as utilization approaches one), and are computed using a distributed iterative scheme. Average flow rates are considered in [5] where the operation of the Internet is modeled as a resource allocation problem with servers supporting a number of priorities. Decentralized methods can be used to obtain stochastic equilibrium which leads to optimal resource allocation. Also related is the application of microeconomic algorithms for flow control, [4, 10]. Finally, a pricing framework for social welfare optimization in the case of guaranteed services with dedicated allocation of resources is described in [7]. The theoretical results presented in this paper are based on that framework.

Our focus in this paper is on usage charges[2] which can provide valuable feedback for guiding future capacity expansion. We describe a pricing scheme for ABR services which is justified from the microeconomic theory of social welfare optimization. Although pricing for optimizing social welfare is desirable, optimality might be outweighed by a high complexity of the required accounting and billing system. The proposed scheme takes advantage of mechanisms provided by rate-based flow control as defined by the ATM Forum, and works complementarily to it. Whereas flow control has the objective of preventing congestion, combining it with pricing leads additionally to economically efficient resource usage. Charges depend directly on bandwidth usage. This is justified by observing that the primary performance measure perceived by users of best-effort services is the transfer delay of objects such as files, images, web pages, etc. In a first approximation, this delay is inversely proportional to the bandwidth used for the transmission. According to the scheme, a connection is charged based on the sum of the price per unit of bandwidth on all links along its route. Prices depend on the demand for band-

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[1] ABR connections can also specify a minimum throughput requirement (Minimum Cell Rate - MCR). Pricing such connections is addressed in Section 6.

[2] The cost of providing network services consists, [8], of fixed (or sunk) costs (due to network devices, cable, e.t.c.) and marginal congestion costs (i.e., the cost incurred due to accepting one more call). This paper discusses only the latter. Similarly, we do not discuss per-call fees for Switched Virtual Connections (SVCs) or connection fees for Permanent Virtual Connections (PVCs).

width and are adjusted in a decentralized and iterative manner. Based on the per unit of bandwidth price posted by the network, users are free to adjust their bandwidth requests throughout the duration of their call. Finally, the computation of usage charges is performed at the periphery of the network.

The rest of this paper is organized as follows. In Section 2 we present some basic results from the microeconomic theory of social welfare optimization and describe the iterative pricing scheme. In Section 3 we briefly describe ATM Forum's rate-based flow control for ABR services. In Section 4 we discuss the implementation of the proposed pricing scheme, and in Section 5 we present related simulation results. Finally, in Section 6 we give some concluding remarks and directions for further research.

2 Pricing for Welfare Optimization

Let L be the set of all network links and C_l the capacity available for ABR traffic traversing link l. We assume that this capacity is either constant or varies slowly[3]. Indeed in an integrated services network, bandwidth will be shared by guaranteed performance CBR and VBR traffic in addition to best-effort ABR traffic, with - possibly - some minimum percentage reserved for the latter. As a result, bandwidth for ABR services can vary depending on the aggregate load of guaranteed performance traffic. However, the aggregation of a large number of connections is likely to make our assumption of constant or slowly varying bandwidth available for best-effort services realistic[4].

Let VC be the set of connections in the network. Based on the common economic assumption of diminishing return when more service (bandwidth) is provided, we assume that each connection c has a bandwidth demand equal to $D_c(w_c) = v_c exp(-w_c)$, where w_c is the price per unit of bandwidth (per unit of time) charged to the connection and v_c is the bandwidth requested when this price is zero. The latter is equal to the peak rate which is specified at connection setup. Finally, we use R_c to denote the route of connection c.

If x_c, w_c denote the cell rate (actual bandwidth used) and the price per unit of bandwidth being charged to c, then the network revenue is $\sum_c x_c w_c$ and the user surplus is $\sum_c \int_{w_c}^{\infty} D_c(u)du$. The social welfare can then be written as

$$W'(w,x) := \sum_{c\in VC} \int_{w_c}^{\infty} \min(x_c, D_c(u))du + \sum_{c\in VC} x_c w_c. \tag{1}$$

Define equilibrium as a state where user demands are met (i.e., $x_c = D_c(w_c)$) and the network maximizes its revenue. From the part of the network, this is clearly a desirable state of operation. If a is the vector of prices on all links, we have the following.

Corollary 1 $\{w_c, x_c : c \in VC\}$ is an equilibrium if and only if there exists a price vector a such that

$$x_c = v_c exp[-w_c], \quad \forall c \in VC \tag{2}$$
$$\sum_{c:l\in R_c} x_c \le C_l, \quad \forall l \in L \tag{3}$$
$$w_c = \sum_{l\in R_c} a_l, \quad \forall c \in VC \tag{4}$$
$$a_l(C_l - \sum_{c:l\in R_c} x_c) = 0, \quad \forall l \in L. \tag{5}$$

This follows directly from proposition 1 in [7]. It is also proved that the equilibrium is unique and maximizes W' given by (1). From (1), (2), and (4) the maximum welfare can be written as

$$W = \sum_{c\in VC} x_c + < a, C > .$$

From (2), (3) and the convexity of $G(a)$ it follows (see [7]) that the maximum welfare can be written as

$$W = \min_{a\ge 0} G(a), \tag{6}$$

where $G(a) = \sum_{c\in VC} v_c exp[-\sum_{l\in R_c} a_l] + < a, C >$.

2.1 The iterative pricing scheme

In order to optimize social welfare, the network must select prices according to (6). A necessary condition for the minimum of $G(a)$ is

$$\frac{\partial G}{\partial a_l} = C_l - \sum_{c:l\in R_c} D_c = 0, \quad \forall l \in L \text{ with } a_l \ne 0. \tag{7}$$

Hence, the minimization of (6) can be performed decentralized: at each link l, the price per unit of bandwidth a_l is increased or decreased if $C_l < \sum D_c$ or $C_l > \sum D_c$, respectively. Each link updates its price in fixed intervals of duration T. We call these *charging intervals* and denote them by $n = 1, 2, \ldots$. The selection of T depends on how fast the aggregate traffic changes and can be dynamically adjusted based on on-line measurements. In any case, it should not be less than the interval from the time a switch posts new prices until the time users' responses to these prices arrive at the switch, i.e., one round-trip delay.

From equation (4), the price per unit of bandwidth w_c^n for connection c during charging interval n is the sum of the prices a_l^n on all links along its route. It is interesting to note that in the state of optimal social welfare the prices are determined by the congested links. Looking at (5), this is an interpretation of the following:

- $a_l = 0$ for the non-congested links ($\sum D_c < C_l$), and

[3] Slowly relative to the time needed for the pricing scheme and flow control to converge.

[4] In any case, as with flow control, the behavior of pricing schemes when this capacity is variable is an important issue.

- $a_l \neq 0 \wedge C_l = \sum D_c = \sum x_c$ for the congested links.

If $x_c(t)$ is c's sending rate at time t, then the charge for interval n is

$$\text{Charge} = w_c^n \int_{(n-1)T}^{nT} x_c(t)dt = w_c^n \bar{x}_c^n T = w_c^n V_c^n, \quad (8)$$

where $\bar{x}_c^n$ is connection c's mean rate (in cells per second) during charging interval n, and V_c^n is the number of cells sent by connection c in interval n.

3 Rate-based Congestion Control

Rate-based flow control is the congestion control scheme for ABR traffic adopted by the ATM Forum ([1, 2]). It is a closed-loop feedback control scheme according to which the network and destinations send congestion feedback information to the sources which react appropriately. All rate-based schemes fall within two categories: binary feedback and explicit rate schemes. In the first category, feedback information occupies a single bit, whereas in the second the network/destination send the source an explicit rate it is allowed to send with. Next we describe the basic functionality of the explicit rate schemes.

Every source periodically sends Resource Management (RM) cells[5]. When the destination receives RM cells, it sends them back to the source (possibly adding an explicit rate at which it can accept information). Intermediate switches monitor their output links to detect congestion. A switch can detect congestion either from the length of its queues or if the total cell incoming rate (over some interval) is larger than the link's capacity. If a switch detects congestion, it sets a congestion indication bit and places an explicit rate ER in the backward RM cells[6] traversing that link. While it does not receive RM cells or receives RM cells with the congestion indication bit set, the source decreases its cell rate by some percentage (multiplicative decrease). If the source receives an RM cell with the congestion indication bit cleared, it is allowed to increase its cell rate by some additive quantity (additive increase). If an RM cell is received with an explicit rate ER lower than the source's current cell rate, the source must reduce its rate to a value less than ER. It is important to note that rate-based schemes require that sources conform to the specified behavior which was just outlined. If this is not the case, cell loss will result not only for the non-conforming connections, but also for the well behaved ones[7]. This makes it necessary to police connections in the entrance of a public network.

[5] Actually recommendations specify, [1], that sources send one RM cell after a specific number of data cells have been sent (counter-based behavior). In this paper we consider the interval-based behavior which is frequently adopted for analytical convenience.

[6] Backward RM cells are those which are traveling towards the sources.

[7] This can be avoided if switches implement a fair-share scheduling algorithm, e.g., round-robin, and per-vc queueing.

Although not part of the recommendations, all algorithms for computing the explicit rate try to fairly allocate bandwidth (e.g., based on max-min fairness, [6]). However, fair allocation of bandwidth does not necessarily mean that it is efficiently utilized from an economic viewpoint. This is the role of pricing.

4 Implementation

In addition to performing all functions related to flow control, switches adjust the price of bandwidth for each of their output links according to the demand. Specifically, for link l the price per unit of bandwidth a_l^n during charging interval n is given by

$$a_l^n := \begin{cases} \max\left\{(1 + h\frac{\sum_{c:l\in R_c} D_c^{n-1} - C_l}{C_l})a_l^{n-1}, 0\right\} & \text{if } a_l^{n-1} \neq 0 \\ \max\left\{k\frac{\sum_{c:l\in R_c} D_c^{n-1} - C_l}{C_l}, 0\right\} & \text{if } a_l^{n-1} = 0 \end{cases} \quad (9)$$

where C_l is the capacity of link l, D_c^{n-1} is the demand for bandwidth by connection c, and $a_l^0 = 0$ for all $l \in L$. Parameter k is a measure of the magnitude of the increase when the price is zero, and h is a measure of how much prices change at each update.

Two pricing specific fields are added to the RM cell. The first contains the requested bandwidth (demand) and the second the price per unit of bandwidth, Figure 1. Based on the price announced by the network, the user of each connection c specifies a requested bandwidth D_c^{n-1}. These values are used by all switches along its route to compute the new price per unit of bandwidth a_l^n using (9). The switch adds this price to the amount contained in the price per unit of bandwidth field of the backward RM cells traversing link l.

With the above scheme, an RM cell that has returned to the source contains the sum of the prices per unit of bandwidth on all links the corresponding connection traverses. This sum is the price w_c^n which is used to compute the charge for interval n using (8). Charges are computed by a policing and billing unit located at the network access point, Figure 1. As discussed in Section 3, besides computing charges, this device is also needed to ensure users conform to the congestion feedback signals they receive from the network.

Based on the prices returned via RM cells, users/sources can modify their bandwidth requests throughout the duration of their connection. This does not require interaction with the real user, but can be implemented automatically by some agent which is provided with the demand function describing the user's preferences.

5 Simulation Results

The goal of our simulation experiments was to study the convergence properties and transient behavior of the proposed pricing scheme, and its interaction with rate-based flow control. Rather than simulating the network

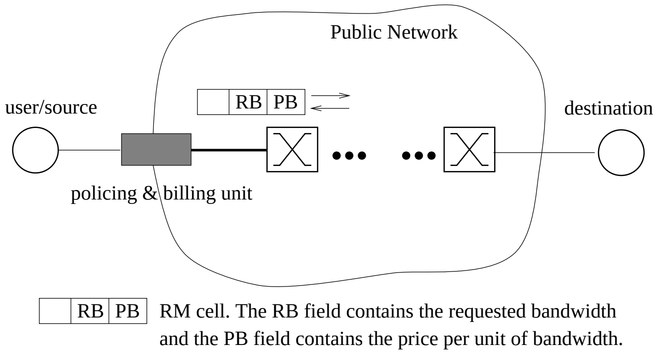


Figure 1: Pricing and billing architecture. The pricing & billing unit calculates charges using the price in the PB field and the number of cells sent in the corresponding charging interval using (8).

at the cell level, we have modeled the propagation of rate changes and the propagation of resource management cells, thus achieving considerably smaller simulation times. The simulated network is shown in Figure 2. All link rates are 155 Mbps. In the three experiments we present here, interswitch distances were 1 km, 100 km, and 1000 km, respectively. Hence we can observe the transient behavior in both a local and wide area environment.

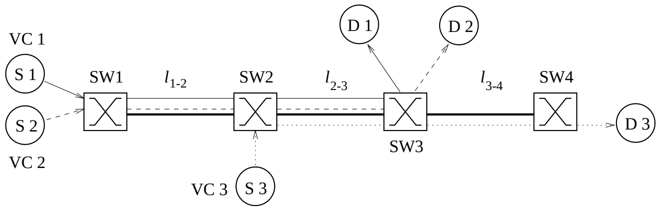


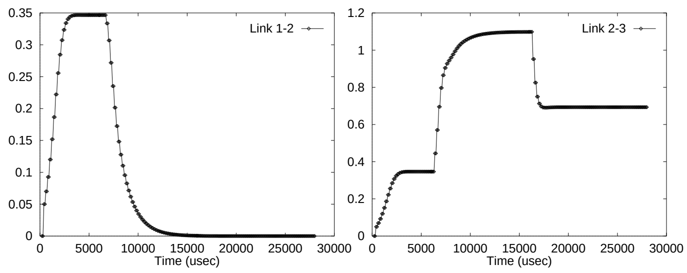
Figure 2: Simulated network.

Sources are assumed to be greedy, i.e., they always wish to send at Peak Cell Rate (PCR) equal to 155 Mbps. Resource management cells are sent periodically every 200 μs. When the source receives a backward RM cell indicating that there is no congestion, it is allowed to increase its rate by the quantity PCR/16 (additive increase). In the other case, it decreases its rate by 1/16 (multiplicative decrease). At all times, the source's sending rate is less than the explicit rate contained in the RM cell that was received last. A source's demand for bandwidth $D_c(w)$ is exponentially decreasing with the price of bandwidth, i.e., $D_c(w_c) = v_c \exp\{-w_c\}$, where v_c=PCR=155 Mbps and w_c is the price per unit of bandwidth. On the switch side, the rate control functions are those of the ERICA (Explicit Rate Indication for Congestion Avoidance) scheme described in [1].

In the first experiment the distance between switches was 1 km and the charging interval 200 μs. Parameters h and k in (9) were 0.4 and 0.05, respectively. It was observed that h determined the number of round-trip times needed for prices to converge (on the contrary, the number of round-trips was independent of the round-trip delay). Also, larger values of h (>1) could lead to oscillations. Although important, a detailed discussion of which values for h lead to good convergence behavior falls outside the scope of this paper. We simply note that the selection depends on the number of multiplexed Virtual Channels (VCs), the magnitude of changes relative to link capacity, network topology, and the sources' demands. The simulation results showed that there is virtually no effect of the pricing scheme on link utilization. Also, the time it took for the VC rates to converge was not affected by the pricing scheme. Figure 3 shows that prices converge quickly after changes of the input traffic.

In the second experiment, the distance between switches was 100 km and the charging interval 2.5 ms. Parameter h in equation (9) was 1.0 while k remained the same as before (= 0.05). As in the previous case, the pricing scheme had no effect on flow control. From Figure 4(α), we see that prices converge. However, convergence times ($\approx$ 20 ms) are greater than the case of 1 km links ($\approx$ 4 ms). In practice, this might not necessarily be a problem since in wide area networks, due to high aggregation of traffic, changes are expected to be smaller and less frequent.

Finally, the dynamic behavior of prices when the distance between switches is 1000 km is shown in Figure 4(β). The charging interval here was 21 ms. Both experiments of Figures 4(α) and 4(β) reached the first equilibrium state after the same (approximately seven) number of iterations. However, convergence time is longer when interswitch distances are larger. This is due to the larger pricing interval (2.5 ms for 100 km links and 21 ms for 1000 km links) which is imposed by the longer round-trip delay.

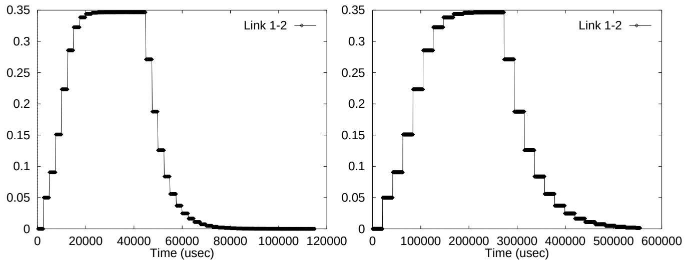


(α) Price at link $l_{1\rightarrow 2}$. (β) Price at link $l_{2\rightarrow 3}$.

Figure 3: Distance between switches is 1 km. VC 1 started at 0 ms and terminated at 16 ms, VC 2 started at 0 ms, and VC 3 at 6 ms. Converge time is $\approx$ 4 ms.

6 Conclusion

We have described a theoretically sound pricing scheme for ABR services, and discussed its implementation using mechanisms provided by rate-based flow control as defined by the ATM Forum. Since the scheme utilizes such mechanisms, there is no additional communication overhead, while the added complexity at the switches and end-systems is minimal. We have also addressed the issue of dynamic behavior of the scheme and presented



(α) Interswitch distance is 100 km. Convergence time is ≈ 20 ms.

(β) Interswitch distance is 1000 km. Convergence time is ≈ 200 ms.

Figure 4: Price at link $l_{1\to 2}$ when the distance between switches is 100 km and 1000 km, respectively. VC 1 and 2 started at 0 ms, and VC 3 at 40 ms.

simulation results showing that the pricing scheme has no negative effect on the speed of convergence and the obtained throughput of flow control. Ongoing work includes experiments with alternative user-demand functions and the case of counter-based source behavior.

In the proposed scheme, senders are charged. By reversing the flow of prices and demands, the scheme can be used to charge the destinations (receivers). In this case, destinations (as opposed to sources in the case of sender charging) send their demands in response to prices they receive from the network. Sources simply shape their output according to the demand they receive from their destinations via RM cells. Charges are computed at the access point of the receiver. In the area of multicast connections where receivers are charged, the distribution of prices among the receivers poses some interesting open questions which require further research.

A problem with all iterative update schemes is the long convergence time when the round-trip delay is large. A scheme which removes the need for iterations altogether is a "smart market" biding for bandwidth. In [8], such an approach was proposed to individually charge the transport of every packet. When applied for pricing bandwidth, users are required to place a bid (or willingness to pay) in addition to the amount of bandwidth they request. This bid is an upper bound on the price per unit of bandwidth according to which they will be charged. Similar to the iterative scheme we presented, prices are zero when there is no congestion. On the other hand, in the presence of congestion, users are allocated bandwidth in the order of decreasing bids. The price for bandwidth at a link is the lowest bid of all requests that were accepted at that link. The advantage of this approach is that optimal prices are computed as soon as requests, along with their respective bids, arrive at a switch (hence no iterative adjustment of prices is required). Its disadvantage is the additional complexity in the switches, since bandwidth allocation depends on users' bids.

Finally, in an extended version of this paper we will show how one can generalize the ideas presented here in order to implement a broad class of models involving congestion pricing, where a user is charged according to the Minimum Cell Rate (MCR) he purchases and the extra rate he introduces in exceedance of MCR. In the above system, congestion is encountered by the cells in excess of MCR, and the pricing model will make the system operate in a socially optimal fashion for appropriately defined user benefit functions.

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