Simple tariffs based on price multipliers for ATM VBR services

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Abstract

We present an approach for constructing simple time-based tariffs for Variable Bit Rate (VBR) connections from Constant Bit Rate (CBR) prices, using price multipliers that depend on the traffic parameters of the VBR connection and reflect the resource usage of VBR connections relative to CBR connections. Our approach employs an effective bandwidth bound as a proxy for the maximum amount of traffic that conforms to the connection's traffic contract, and thus for the maximum resource usage. We compare the price multipliers computed using our approach with the multipliers published by an actual ATM service provider, and with those computed using a proxy for resource usage that is based on ATM Forum's Generic CAC algorithm. Although our approach is presented in the context of ATM VBR services, it can be applied for creating tariffs for Service Level Agreements (SLAs) where the maximum amount of conforming traffic is given by leaky (or token) bucket constraints.

Keywords: charging, leaky bucket, effective bandwidth, service level agreement

1 Introduction

We address the problem of charging ATM Variable Bit Rate (VBR) connections. Associated with such connections is a traffic contract that specifies the maximum amount of traffic (traffic profile) the user (customer) can send into the network, and the quality of

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service that the network provider commits to guarantee for the portion of the user's traffic that conforms to his traffic profile. The source traffic parameters of a VBR traffic contract include the peak cell rate (PCR), the sustainable cell rate (SCR), and the maximum burst size (MBS) [10].

Our focus is on the per unit of time charge for VBR connections. In addition to these charges, network service charges can include an access rental that a customer pays in fixed time periods (e.g., per month), independent of the virtual connections utilized, and a fixed charge for setting up new connections. The per unit of time charge of a connection should depend on the quality of service guarantees and the maximum amount of traffic that conforms to the connection's traffic contract. British Telecommunications (BT) CellStream ATM service defines VBR Permanent Virtual Connection (PVC) prices based on Constant Bit Rate (CBR) prices, using price multipliers that depend on the burst ratio PCR/SCR and the maximum burst size MBS. Such an approach has the advantages of compactness and simplicity, since VBR prices become easy to compute, and users understand how the parameters of their traffic contract affect prices, hence the task of selecting the traffic parameters that minimize their charge becomes simpler.

The contribution of this paper is twofold. First, we present and investigate an approach for constructing simple *time-based* tariffs for VBR connections from CBR prices, using *price multipliers* that depend on the traffic parameters of the VBR connection and reflect the resource usage of VBR connections relative to CBR connections. We argue that, if peak rates are close, or are much smaller than the link capacity, then price multipliers can be defined in terms of the ratio PCR/SCR, rather than the absolute values of SCR and PCR, without compromising their fairness or incentive properties. Second, we compare the price multipliers derived using an effective bandwidth bound as a proxy for resource usage with the multipliers published by BT, and with those computed using a proxy for the maximum resource usage that is based on ATM Forum's Generic Connection Admission Control (GCAC) algorithm. Our comparisons indicate that BT's tariffs are not in disagreement with those computed based on resource usage but, on the contrary, appear to express usage similarly to the effective bandwidth approach when there is a low degree of statistical multiplexing. Comparison of tariffs based on effective bandwidths with BT's tariffs has also been discussed in [16]. The focus there was on resource usage, whereas in this paper the focus is on the comparison in terms of price multipliers. Additionally, through the comparison of the various approaches, we discuss how the link resources and the traffic contract parameters should affect resource usage, hence the price multipliers.

With time-based tariffs, charges depend solely on the parameters of the traffic contract, and do not take into account the traffic actually sent. As discussed in [4, 5], such a charging scheme does not discourage users from sending the maximum amount of traffic that conforms to their contract, which can be considerably more than the traffic they actually need to send. Of course, if the traffic actually sent is close to the maximum allowed by the traffic contract, then time-based charges can accurately reflect the relative amount of actual resource usage. In any case, time-based charging schemes are attractive, particularly when ATM services are first offered, since they require neither traffic measurements nor complex accounting mechanisms, and are simpler for users to understand.

We do not address the issue of how CBR prices are determined; in addition to resource usage, these prices will depend on the price of other similar or substitutable services, such as leased lines and frame relay services, and on economic factors, such as demand, market segmentation, and bulk discounts. Of course, VBR prices will also depend on the above factors. Nevertheless, economic theory suggests that the relative prices of connections targeted to the same market segment should reflect, to a large extent, the relative amount of resources used by these connections. An objective of this paper is to capture and investigate exactly this effect of relative resource usage on prices, hence on price multipliers.

As discussed above, we address the problem of how to derive relative prices of traffic contracts based on the relative amount of resources they can use. Hence, our work differs from [12, 13], which study optimal pricing strategies when network resources (capacity and buffer) are charged separately, from [7], which also assumes that traffic parameters are charged independently, without taking into account their effect on resource usage, and from [2, 14], which address architectural issues related to pricing of network services.

The rest of this paper is structured as follows. In the remainder of this section we present BT's price multipliers for VBR services (Section 1.1). In Section 2 we present our approach for computing price multipliers using an effective bandwidth bound as a proxy for the maximum amount of resources that can be used by a VBR connection. Next, we compare the price multipliers computed using the effective bandwidth approach with the multipliers published by BT (Section 3), and with those computed using a proxy for resource usage that is based on ATM Forum's Generic CAC algorithm (Section 4). Finally, in Section 5 we present some concluding remarks.

1.1 BT's price multipliers for VBR connections

BT's prices for VBR connections are computed from CBR prices using price multipliers [1], which depend on the burst ratio PCR/SCR and the maximum burst size MBS. This can be expressed as follows

$$P_{\mathrm{VBR}} = M_1(PCR/SCR) \cdot M_2(PCR/SCR, MBS) \cdot P_{\mathrm{CBR}} \,,$$

Table 1: BT's price multipliers.

Burst ratio (PCR/SCR)	1	2	5	10	15	20
Multiplier	0.9	1.1	1.5	2.0	2.3	2.5

(a) Multiplier M_1 for the burst ratio PCR/SCR

MBS (in cells)	50	100	200
Multiplier ($PCR/SCR \geq 1.8$)	0.85	0.9	1.0
Multiplier ($PCR/SCR < 1.8$)	1.0	1.0	1.0

(b) Multiplier M_2 for MBS

where P_{CBR} is the price per unit of time for a CBR connection with peak rate equal to the sustainable cell rate SCR of the VBR connection. Note that in the above formula both multipliers depend on the burst ratio PCR/SCR, rather than on the absolute values of PCR and SCR. We will discuss this in more detail in the next section.

The values of BT's price multipliers are shown in Table 1. The price multiplier for burst ratios not shown in Table 1(a) are computed using linear interpolation between the closest values below and above the requested ratio.

We conclude this section with two observations regarding BT's price multipliers. First, observe that for burst ratio equal to 1, the price for a VBR connection is 0.9 times the price for a CBR connection with peak rate equal to SCR; the latter is equal to PCR, since the burst ratio is 1. Hence, the price for a VBR connection can be *lower* than that of a CBR connection with the same throughput. As noted in [16], this can only be justified if the quality of the VBR service is lower than that of the CBR service. This is the case with non real-time VBR services. Second, observe that the price multipliers are in reference to $MBS = 200$, since $M_2(PCR/SCR, MBS = 200) = 1$.

2 Price multipliers based on effective bandwidths

In this section, based on effective bandwidths, we present a bound that employs a leaky (or token) bucket descriptor for characterizing the maximum amount of conforming traffic, we discuss how VBR traffic contract parameters can be mapped into leaky bucket parameters, and finally we present an approach for computing price multipliers from the effective bandwidth bound. Note that, although the method for computing price multipliers is quite sophisticated, it is applied only by the network provider; customers are presented with relatively simple tariffs, having a form similar to Table 1.

2.1 Effective bandwidth as a measure of resource usage

Extensive research has been done on how to quantify resource usage in broadband networks. This research has shown that, if some kind of quality of service is guaranteed, then a connection's resource usage depends not only on the statistical characteristics of the connection's traffic, but also on the link resources (capacity and buffer) and the characteristics of the other multiplexed traffic.

The authors of [11, 4] propose an effective bandwidth definition where the connection's multiplexing context is encoded in just two parameters, the *space* and *time* parameters s, t, which depend on the link resources (capacity and buffer) and the characteristics of the multiplexed traffic. Investigations with real broadband traffic have shown that this effective bandwidth definition is quite accurate when the number of multiplexed connections is large [6]. Furthermore, these investigations have also shown that the parameters s, t are to a large extent insensitive to small variations of the traffic mix. Hence, for given link resources, pairs of s, t can be assigned to periods of the day during which the traffic mix remains relatively constant. The parameters can be computed off-line from actual traffic traces.[1]

An upper bound of the effective bandwidth of a connection with mean rate m and traffic contract $\mathbf{x} = \{h, (\rho, \beta)\}$, where h is the peak rate and (ρ, β) are the leaky bucket parameters, is the so-called "simple" bound [4, 3] given by

$$\bar{\alpha}(\mathbf{x}, m) = \frac{1}{st} \log \left[1 + \frac{m}{H(t)} \left(e^{stH(t)} - 1 \right) \right] ,$$

where $H(t)t = \min\{ht, \rho t + \beta\}$ is the maximum amount of traffic that can be sent in a time interval of duration t; $H(t)$ thus represents the effective peak of the traffic contract in a time-scale t. An upper bound of the mean rate m is the leak rate ρ. Hence, an upper bound of the maximum amount of traffic that conforms to the contract $\mathbf{x} = \{h, (\rho, \beta)\}$ is

$$EB(\mathbf{x}) \overset{\text{def}}{=} \frac{1}{st} \log \left[1 + \frac{\rho}{H(t)} \left(e^{stH(t)} - 1 \right) \right] = \bar{\alpha}(\mathbf{x}, \rho) \geq \bar{\alpha}(\mathbf{x}, m) , \qquad (1)$$

where again $H(t) = \min\{h, \rho + \beta/t\}$.

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[1] Related software for computing these parameters and typical values for various link capacities, buffer sizes, and types of traffic can be found in [15].

2.2 VBR traffic contract and leaky bucket parameters

The compliance of an ATM connection to its traffic contract is verified using the Generic Cell Rate Algorithm (GCRA) which determines, for each arriving cell, whether the cell conforms to the traffic contract or not [10]. The parameters of the GCRA depend on the three source traffic descriptors for VBR connections: the peak cell rate (PCR), the sustainable cell rate (SCR), and the maximum burst size (MBS). For simplicity, we do not consider the Cell Delay Variation Tolerance ($CDVT$) [10], since this is a connection traffic parameter that cannot be varied by the user and will typically be very small.

For PCR, the leaky bucket parameters that correspond to the above conformance definition are

$$(h, 1) = (PCR, 1)\,.$$

For the GCRA that polices SCR, one can show that if the maximum number of conforming back-to-back cells is MBS, then the bucket size must equal $(MBS-1)(1-SCR/PCR)+1$. Hence, the leaky bucket for SCR is

$$(\rho, \beta) = (SCR, (MBS-1)(1-SCR/PCR)+1)\ ,$$

where MBS is expressed as number of cells.

In the above derivation of the leaky bucket parameters for PCR and SCR, we took into account the discrete nature of the GCAC algorithm, since in ATM networks data is segmented and transmitted in fixed size cells. However, for the investigations in the rest of this paper the discrete nature of the GCAC algorithm is not significant. Hence, for simplicity, we use the following fluid approximations of the leaky bucket parameters

$$(h, 0) = (PCR, 0) \quad \text{and} \quad (\rho, \beta) = (SCR, MBS(1-SCR/PCR))\ . \tag{2}$$

2.3 Definition and computation of price multipliers

In this subsection we present two approaches for expressing prices for VBR connections in terms of CBR prices using price multipliers. Both approaches are based on the effective bandwidth bound introduced above. The first approach employs a single price multiplier that captures the dependence of resource usage on both the burst ratio PCR/SCR and the maximum burst size MBS. The second approach employs two price multipliers: the first captures the dependence of resource usage on the ratio PCR/SCR, and the second captures the dependence of resource usage on MBS.

2.3.1 Single price multiplier approach

As discussed in Section 2.1, the effective bandwidth of a connection depends on the link's operating point through two parameters s, t. In the investigations that follow, unless otherwise noted, we use the values $s = 10$ Mbit^{-1} and $t = 0.1$ sec, which are typical for a link with capacity 155 Mbps and buffer 1500 cells serving a mix of MPEG-1 compressed video and voice traffic with a guaranteed buffer overflow probability 10^{-8} [15]. Note that the peak rate of such traffic is typically at least two orders of magnitude smaller than the link capacity we consider (155 Mbps).

Recall that our objective is to have the relative prices of VBR and CBR connections reflect the relative amount of resources that can be utilized by each. The maximum amount of resources for a VBR connection with parameters PCR, SCR, and MBS is $EB(PCR, SCR, MBS)$, which is computed from equations (1) and (2). On the other hand, the amount of resources used by a CBR connection with peak rate equal to PCR is simply PCR. Hence, to reflect the relative amount of resources, the price per unit of time P_{VBR} for a VBR connection should be given by

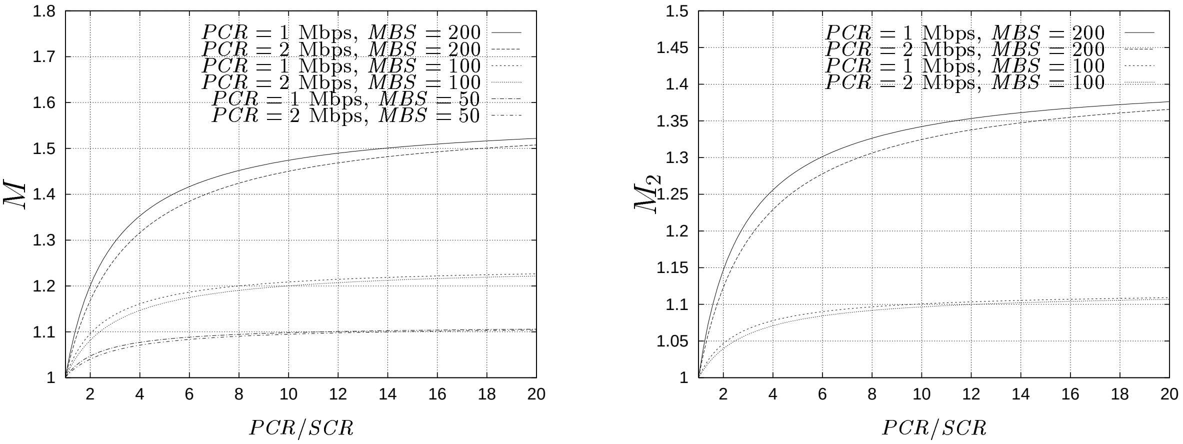
$$\begin{aligned} P_{\text{VBR}} &= \frac{EB(PCR, SCR, MBS)}{SCR} \cdot P_{\text{CBR}} \\ &= M(PCR, SCR, MBS) \cdot P_{\text{CBR}}\,, \end{aligned} \tag{3}$$

where P_{CBR} is the price of a CBR connection with peak rate equal to SCR.

Figure 1(a) shows the values of M, obtained by equation (3), for $PCR = 1$ and 2 Mbps and $MBS = 50, 100,$ and 200 cells; note that, for each value of PCR, the values of M are depicted as a function of PCR/SCR rather than as a function of SCR alone. First, observe that for $PCR/SCR = 1$ all curves in Figure 1(a) take the value 1. This is expected, since the effective bandwidth, hence resource usage, of a VBR connection with $PCR = SCR$ is equal to that of a CBR connection with rate PCR. Second, observe that, for a fixed value of MBS, the multiplier M has very limited dependence on PCR, whereas it depends heavily on PCR/SCR. In fact, the dependence on PCR is smaller when PCR/SCR is close to 1 or is large. This result can be derived analytically as follows. Recall that the effective bandwidth bound $EB(\mathbf{x})$ in (1) is a function of $H(t) = \min\{h, \rho + \beta/t\}$. For the values considered, the effective peak is

$$H(t) = \rho + \beta/t = SCR + MBS(1 - SCR/PCR)/t\,.$$

As $PCR/SCR \to 1$, or equivalently as $\rho = SCR \to PCR$, both the effective peak $H(t)$ and the effective bandwidth in (1) tend to PCR, hence the ratio $EB(PCR, SCR, MBS)/SCR$ tends to 1. On the other hand, as $SCR \to 0$ the effective peak tends to MBS/t. Using this



(a) Price multipliers for PCR/SCR

(b) Price multipliers for MBS

Figure 1: EB-based price multipliers. In figure (a), which shows the multiplier M given by (3), the three pairs of curves from bottom to top are for $MBS = 50, 100,$ and 200 cells. In figure (b), which shows the multiplier M_2 given by (5), the two pairs of curves are for $MBS = 100$ and 200.

result, one can show that as $SCR \to 0$ the limit of the ratio $EB(PCR, SCR, MBS)/SCR$, with $EB(PCR, SCR, MBS)$ given by (1), depends on SCR and PCR only through the burst ratio PCR/SCR.

Based on the previous discussion and the results of Figure 1, for the link capacity considered (155 Mbps), when the peak rates of the connections are in the range $1-2$ Mbps, it is reasonable to define VBR tariffs using multipliers that depend on MBS and on the pair SCR, PCR only through the burst ratio PCR/SCR. This can considerably simplify the presentation of the tariffs, thus facilitating the choice of the optimal traffic contract parameters by the user. Note that, for the values of PCR and MBS considered, the maximum error of this approach is less than 3%. Similar error bounds were obtained in additional numerical investigations where again the peak rates of connections were at least two orders of magnitude smaller than the link capacity. Hence, in such cases the price multiplier M can be expressed as a function of the form $M(PCR/SCR, MBS)$.

For each value of MBS that is offered, the price multiplier M can be presented in the form of a table, similar to BT's multipliers for the burst ratio in Table 1(a): the multipliers for specific values of the ratio PCR/SCR are given in the table, while the multipliers for intermediate values can be computed using linear interpolation. Hence, if three values of MBS are offered, then there will be three tables similar to Table 1(a). Each such table can be derived from a pair of almost coinciding curves, such those in Figure 1(a).

2.3.2 Dual price multiplier approach

Rather than employing a single multiplier $M(PCR/SCR, MBS)$, an alternative approach is to define two multipliers, M_1 and M_2, which capture the effects of PCR/SCR and MBS, respectively. From (3), and taking $MBS = 50$ as a reference value, we have

$$\begin{aligned} P_{\mathrm{VBR}} &= \frac{EB(PCR, SCR, MBS)}{SCR} \cdot P_{\mathrm{CBR}} \\ &= \frac{EB(PCR, SCR, MBS = 50)}{SCR} \cdot \frac{EB(PCR, SCR, MBS)}{EB(PCR, SCR, MBS = 50)} \cdot P_{\mathrm{CBR}} \\ &= M_1 \cdot M_2 \cdot P_{\mathrm{CBR}} \,. \end{aligned}$$

Under the above approach, the multiplier $M_1(PCR/SCR)$ is defined in reference to some particular value of MBS, which in the above equation was taken to be $MBS = 50$. Hence,

$$M_1(PCR/SCR) = \frac{EB(PCR, SCR, MBS = 50)}{SCR} \,. \tag{4}$$

Values of $M_1(PCR/SCR)$ are shown in Figure 1(a); they correspond to the bottom pair of curves. As was the case with the multiplier M in the single multiplier approach, the multiplier $M_1(PCR/SCR)$ can be presented in the form of a table, similar to BT's multipliers for the burst ratio shown in Table 1(a): the multipliers for specific values of the ratio PCR/SCR are given in the table, while the multipliers for intermediate values of the ratio can be computed using linear interpolation.

The second multiplier M_2 expresses the resource usage of a VBR connection relative to the resource usage of a connection with $MBS = 50$, while the other traffic parameters remain the same. Hence,

$$M_2(PCR/SCR, MBS) = \frac{EB(PCR, SCR, MBS)}{EB(PCR, SCR, MBS = 50)} \,. \tag{5}$$

Figure 1(b) shows the multiplier M_2 for $MBS = 100$ and 200. As was the case for M_1, the multiplier M_2 depends on SCR and PCR primarily through the ratio PCR/SCR. Indeed, for the values of PCR and MBS considered, the maximum error of this approach is less than 2.5%. The dependence of M_2 on the ratio PCR/SCR indicates that price multipliers for MBS cannot be defined independently of PCR/SCR. Hence, the multiplier M_2 can be expressed as a function of the form $M_2(PCR/SCR, MBS)$.

The price multiplier $M_2(PCR/SCR, MBS)$ can be presented in the form of a table, similar to the presentation of $M_1(PCR/SCR)$. This would result in a total of three tables: one for the multiplier $M_1(PCR/SCR)$ and two for the multiplier $M_2(PCR/SCR, MBS)$, corresponding to the values $MBS = 100$ and 200 cells (by definition, $M_2(PCR/SCR, MBS =$

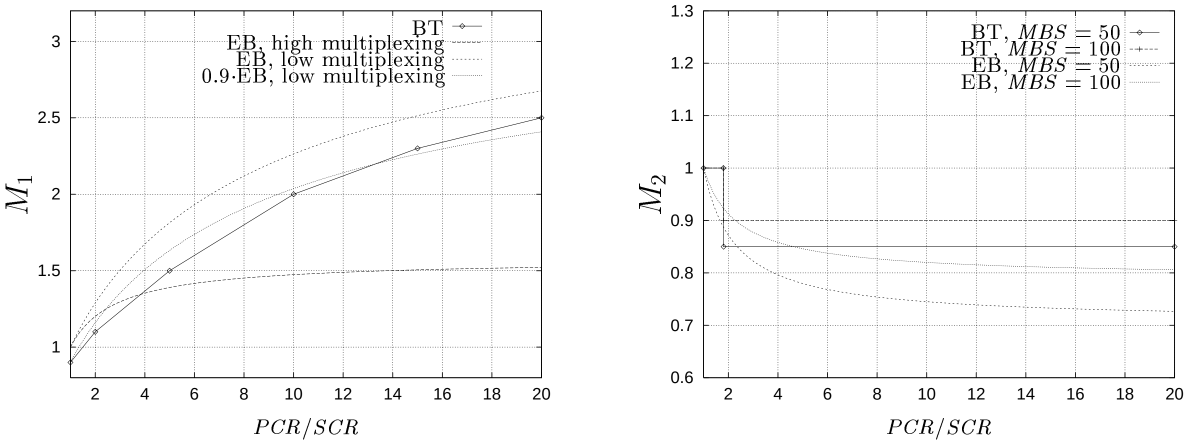
50) = 1). An alternative to the above is to consider a step-wise approximation of the two curves in Figure 1(b). This is the approach taken in defining BT's price multipliers for MBS that are shown in Table 1(b). As we further discuss in the next section, such a step-wise approximation is less accurate than a piece-wise linear approximation, but allows the two multipliers for $MBS = 100$ and 200 to be presented in a single, compact table, such as Table 1(b). Finally, we note that if intermediate values of MBS are to be offered, then the corresponding price multipliers can be computed using linear interpolation, as in the case of price multipliers for intermediate values of the burst ratio PCR/SCR. However, $MBS = 50, 100$ and 200 cells are the values offered almost exclusively in practical cases.

3 Comparison of EB-based and BT price multipliers

As already discussed, BT's VBR tariffs are defined using two multipliers: one for the burst ratio and one for the maximum burst size. Note that BT's price multipliers are defined with reference to $MBS = 200$, whereas the EB-based multipliers discussed in the previous section were defined in reference to $MBS = 50$; see equations (4) and (5). The reference value $MBS = 200$ results in the price multiplier M_2 having values in the range $[0.7 - 1.0]$, estimated from Figure 1(b), whereas the reference value $MBS = 50$ results in the price multiplier M_1 having values in the range $[1.00 - 1.11]$, estimated by the lower pair of curves in Figure 1(a). Both approaches are equivalent regarding the methodology for computing the final prices. However, in order to carry out a comparison of BT and EB-based price multipliers, we compute the latter with reference to $MBS = 200$. The comparison is shown in Figures 2(a) and 2(b). Also, Table 2 presents the EB-based multipliers derived from the previous figures in a form identical to that of BT's multipliers in Table 1. Next, we make some observations regarding Figures 2(a) and 2(b), and Table 2.

First, observe in Figure 2(a) that BT's multiplier for the burst ratio can take values less than 1. A value less than 1 results in a VBR connection being cheaper than a CBR connection having the same throughput; e.g., a VBR connection with $SCR = PCR$ is priced at 90% of the price of a CBR connection with the same rate. As indicated in Section 1.1, this can only be justified if the quality of VBR services is lower than that of CBR services.

Second, Figure 2(a) shows that, for small values of PCR/SCR, the multiplier for the burst ratio M_1 is lower for the EB-based approach, for which we have taken $s = 10$ Mbit^{-1} and $t = 0.1$ sec (curve labeled "EB, high multiplexing"), compared to BT's price multiplier. This is also evident from the comparison of Table 2(a) with Table 1(a). However, observe in Figure 2(a) that the shape of the EB-based price multiplier for $s = 25$ Mbit^{-1} and



(a) Price multipliers for PCR/SCR (b) Price multipliers for MBS

Figure 2: Comparison of EB-based and BT price multipliers. In figure (a), observe that BT's price multipliers are close to the EB-based price multipliers for low multiplexing, scaled by a factor of 0.9.

Table 2: EB-based price multipliers with reference value $MBS = 200$.

Burst ratio (PCR/SCR)	1	2	5	10	15	20
Multiplier	1	1.2	1.4	1.45	1.5	1.55

(a) Multiplier M_1 for the burst ratio PCR/SCR

MBS (in cells)	50	100	200
Multiplier ($PCR/SCR \geq 1.8$)	0.88	0.93	1.0
Multiplier ($PCR/SCR < 1.8$)	1.0	1.0	1.0

(b) Multiplier M_2 for MBS

$t = 0.2\,\mathrm{sec}$ (curve labeled “EB, low multiplexing”) is similar to that of BT’s multiplier. In fact, the EB-based multiplier scaled by a factor of 0.9, which is equal to BT’s multiplier for burst ratio $PCR/SCR = 1$, (curve labeled “$0.9 \cdot$ EB, low multiplexing” in Figure 2(a)), is very close to BT’s multiplier. It is interesting to note that the above values of s, t are typical for links that serve connections with peak rates only an order of magnitude smaller than the link capacity, as is the case for $PCR = 1 - 2$ Mbps and link capacity $C = 34$ Mbps, which indeed correspond to a case of low multiplexing. On the other hand, the values $s = 10$ Mbit^{-1} and $t = 0.1\,\mathrm{sec}$ are typical for a link with capacity $C = 155$ Mbps serving connections with peak rates $PCR = 1-2$ Mbps. This observation suggests that a possible reason for having high values for the multiplier M_2 for high burst ratios PCR/SCR when the link capacity is small is that it is difficult to multiplex such bursty connections, which thus require more resources than in a link with higher capacity.

Figure 2(b) shows the EB-based and BT price multipliers for MBS. The latter is defined in Table 1(b) and corresponds to a step-wise function. As Figure 2(b) shows, the step-wise approximation is crude; nevertheless, it has the advantage of allowing the compact representation of Tables 1(b) and 2(b). Finally, similar to our observation regarding the price multiplier for the burst ratio, for a high degree of statistical multiplexing, which is the case for Table 2(b), the price multiplier for MBS tends to be closer to 1, compared to a low degree of statistical multiplexing, which is the case for Table 1(b).

4 Price multipliers based on the Generic CAC algorithm

In this section we apply the approach of Section 2.3 for computing price multipliers, but instead of the effective bandwidth bound, we consider a proxy for resource usage that is based on ATM Forum’s Generic CAC (Connection Admission Control) algorithm [9]. There are two versions of the GCAC algorithm, a simple and a complex one. Both versions consider only the PCR and SCR parameters of the traffic contract, hence in the investigations of this section we do not consider MBS. We use equation (3) for computing the price multiplier, with the effective bandwidth EB replaced by the corresponding measure of resource usage derived using the simple and the complex GCAC, and compare it with the EB-based and BT multipliers, for which we take $MBS = 200$.

The simple GCAC algorithm uses the following measure of the amount of resources

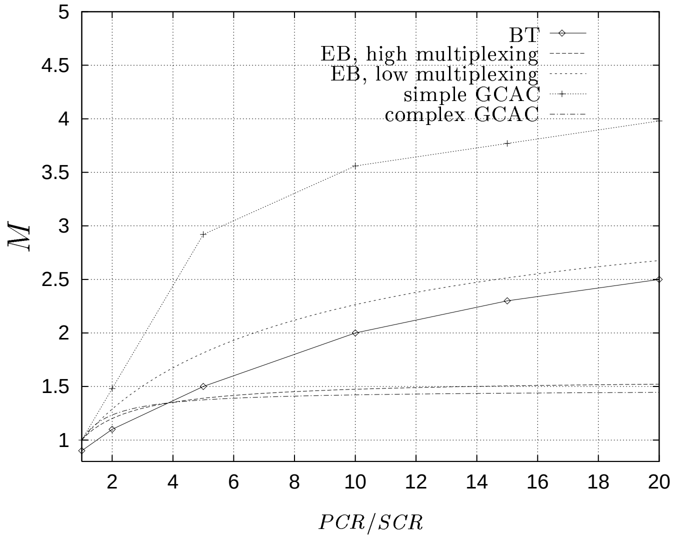


Figure 3: BT, EB-based and GCAC-based multipliers. Higher values of a price multiplier imply a lower multiplexing gain when multiplexing bursty connections.

required by a new VBR connection.

$$B_{\mathrm{s}}(SCR, PCR) = \begin{cases} (0.0145 \cdot x + 4.22)SCR & \text{if } x > 39 \\ (0.042 \cdot x + 3.14)SCR & \text{if } 39 \geq x > 5 \\ (0.48 \cdot x + 0.52)SCR & \text{if } x \leq 5 \end{cases},$$

where x is the burst ratio PCR/SCR. In Figure 3, we compare the price multiplier for the simple GCAC, defined as $M_{\mathrm{s}} = B_{\mathrm{s}}/SCR$, with the EB-based and BT multipliers. The figure shows that for values of PCR/SCR close to 1, the price multiplier computed using the simple GCAC is close to the EB-based and BT price multipliers. On the other hand, for large values of PCR/SCR, i.e., for large values of x, the multiplier using the simple GCAC is considerably higher than that of the other two approaches; this result confirms that the simple GCAC gives a more conservative estimate of the resources used by bursty connections, compared to the corresponding estimate given by the EB-based and BT approaches.

Next, we compute the price multiplier based on the complex GCAC. The complex GCAC employs the notion of the Cell Rate Margin (CRM), which is equal to $AAC - ASR$; the Actual Allocated Capacity (AAC) is the amount of bandwidth that has been allocated to ongoing connections by the actual CAC used in the switches, and the Aggregated Sustained Rate (ASR) is the sum of the SCR's of ongoing connections or some smaller measured or estimated value. Note that CRM is always positive.

Each link advertises the values of CRM_{link} and VAR_{link}. A link has sufficient resources for accepting a new connection with parameters SCR, PCR if and only if

$$SCR + CRM_{\text{new}} - CRM_{\text{link}} \leq C - AAC\,,$$

where C is the link capacity and CRM_{new} is the new value of the cell rate margin if the new connection is accepted. Hence, according to the complex GCAC, the amount of resources required by a new connection is

$$B_{\text{c}}(SCR, PCR) = SCR + CRM_{\text{new}} - CRM_{\text{link}}\,. \tag{6}$$

The basic idea underlying the complex GCAC is that the ratio

$$VF_{\text{link}} = \frac{CRM_{\text{link}}^2}{VAR_{\text{link}}}\,, \tag{7}$$

does not change significantly when one connection is added to the link [9]. In the last equation, VAR_{link} is given by

$$VAR_{\text{link}} = \sum_{i=1}^{N} SCR_i(PCR_i - SCR_i)\,, \tag{8}$$

where N is the number of ongoing connections. From (7) we have that

$$CRM_{\text{new}} = \sqrt{VF_{\text{link}} \cdot VAR_{\text{new}}}\,. \tag{9}$$

From (8) we have $VAR_{\text{new}} = VAR_{\text{link}} + SCR(PCR - SCR)$. Substituting VAR_{new} in (9) we obtain

$$\begin{aligned} CRM_{\text{new}} &= \sqrt{VF_{\text{link}}(VAR_{\text{link}} + SCR(PCR - SCR))} \\ &= \sqrt{VF_{\text{link}} \cdot VAR_{\text{link}}}\sqrt{1 + \frac{SCR(PCR - SCR)}{VAR_{\text{link}}}} \\ &= CRM_{\text{link}}\sqrt{1 + \frac{SCR(PCR - SCR)}{VAR_{\text{link}}}} \\ &\approx CRM_{\text{link}}\left(1 + \frac{1}{2}\frac{SCR(PCR - SCR)}{VAR_{\text{link}}}\right)\,. \end{aligned} \tag{10}$$

The last approximation holds when $SCR(PCR - SCR) << VAR_{\text{link}}$, which is true when a large number of connections are being multiplexed. Combining (6) and (10), we obtain

$$B_{\text{c}}(SCR, PCR) \approx SCR\left(1 + \frac{1}{2}\frac{CRM_{\text{link}}}{VAR_{\text{link}}}(PCR - SCR)\right)\,.$$

Hence, the price multiplier based on the complex GCAC is given by

$$M_{\mathrm{c}} = \frac{B_{\mathrm{c}}(SCR, PCR)}{SCR} \approx 1 + \frac{1}{2}\frac{CRM_{\mathrm{link}}}{VAR_{\mathrm{link}}}(PCR - SCR)\,.$$

From the last equation, observe that the price multiplier computed based on the complex GCAC cannot be written as a function of the ratio PCR/SCR, as in the BT, EB-based, and simple GCAC cases.

As a numerical example, consider the homogeneous case where all connections have $PCR = 1$ Mbps and $SCR = 0.2$ Mbps, which are typical for a connection carrying MPEG-1 compressed video traffic. From (8) we have $VAR_{\mathrm{link}} = N \cdot SCR(PCR - SCR)$, where N is the number of ongoing connections. The value of N depends on the actual CAC implemented in the switches, which in the numerical results we will assume to be based on the effective bandwidth as a measure of resource usage. The value of N is given by the ratio $C/EB(SCR, PCR, MBS)$. For the traffic parameters considered, $PCR = 1$ Mbps and $SCR = 0.2$ Mbps, and for a large value for MBS, we have $EB(SCR, PCR, MBS) = 0.35$ Mbps, from which we obtain $N = 428$. Hence, $VAR_{\mathrm{link}} = 68.5\ \mathrm{Mbps}^2$. Finally, $CRM_{\mathrm{link}} = AAC - ASR = N \cdot EB(SCR, PCR, MBS) - N \cdot SCR = 64.2$ Mbps.

Figure 3 shows the price multiplier based on the complex GCAC, computed for $PCR = 1$ Mbps. An interesting observation is that the multiplier based on the complex GCAC approach is very close to the EB-based multiplier. This is due in part to the use of the effective bandwidth for the actual CAC in the switches, which was used for computing the number N of connections that can be multiplexed. In general, the performance of the complex GCAC depends heavily on the actual CAC mechanism used for admission control algorithm implemented in the switches.

5 Concluding remarks

We have presented an approach, based on price multipliers, for deriving simple time-based tariffs for VBR connections from prices for CBR connections. Our investigations have shown that it is meaningful for price multipliers to depend on the parameters SCR and PCR only through the burst ratio PCR/SCR, when the peak rates PCR are at least two orders of magnitude smaller than the link capacity.

We have compared the price multipliers computed using the effective bandwidth as a measure of resource usage with the price multipliers published by a commercial ATM service provider, namely BT. The comparison indicates that BT's tariffs are not in disagreement with those computed based on resource usage but, on the contrary, appear to express usage similarly to the effective bandwidth approach for the case of low statistical multiplexing. Finally, to demonstrate that the approach for deriving price multipliers is not necessarily tied to effective bandwidths as a measure of resource usage, we have compared the above price multipliers with those derived using ATM Forum's Generic CAC algorithm as a measure of resource usage.

Although our approach is presented in the context of ATM VBR services, it can be applied for defining tariffs for Service Level Agreements (SLAs) where the user's traffic profile is characterized by leaky (or token) bucket constraints. Examples of such services include the controlled-load service [17] in the IETF's Intergrated Services (IntServ) framework, and services in IETF's Differentiated Services (DiffServ) framework that provide probabilistic guarantees and use the token bucket for specifying the temporal properties of the traffic entering the network [8].

A related and interesting issue is to investigate the relative prices of substitutable and/or complementary network transport services, such that one service does not "cannibalize" another. This can be the basis for determining CBR prices, hence complements the work presented in this paper, which gives an approach for determining VBR prices relative to CBR prices.

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