Link Capacity Sharing Between Guaranteed- and Best Effort Services
Extended Abstract

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Abstract

While link allocation policies in multi-rate circuit switched loss models have drawn much attention in recent years, it is still an open question how to share the link capacity between service classes in a fair manner. In particular, when an ATM link is offered calls from service classes with/without strict QoS guarantees one is interested in link capacity sharing policies that maximize throughput and keep the per-class blocking probabilities under some GoS constraints. In this extended abstract we propose a model and associated computational technique for an ATM transmission link to which CBR/VBR and ABR classes offer calls. We also propose a simple link allocation rule which takes into account blocking probability constraints for the CBR/VBR calls and a throughput constraint for the ABR class and attempts to minimize the ABR class blocking probability.

Numerical examples demonstrate the effectiveness of the policy and of the applied computational technique are provided in the full paper version.

Key words: multi-rate loss models, link capacity sharing, blocking probabilities, ATM service categories, Markov Reward Model.

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1 Introduction

In recent years the various aspects of the coexistence of different service classes in ATM gained much attention and significant advances in the management of ATM traffic have been achieved. Most of the ATM traffic management efforts both within the major standardization bodies and the industry have been focusing on the *cell level* aspects of ATM, such as devising efficient congestion control- and policing mechanisms, and also call admission control (CAC), buffer allocation- and cell scheduling rules. Although *call level* issues in the multi-rate environment, like the computation of the blocking probabilities and establishing link capacity sharing policies have also been addressed by many papers, very few paper deals with the problem of blocking probability calculations and link allocation policies when service classes with/without congestion control and with/without cell level QoS guarantees are present in a system simultaneously. The investigation of the call level aspects is important, since the blocking probability constraints are the primary inputs to the network dimensioning process. The hardship of this type of problem lies in the fact that the classical method of the *equivalent bandwidth* connecting the cell- and call level aspects is not directly applicable to an ATM link supporting CBR/VBR and ABR service classes simultaneously. This is because while it has been possible to associate a bandwidth-like quantity even with the VBR class, it is difficult to do the same for the ABR service class, because

- ABR does not provide the same level of QoS as the CBR/VBR classes
- there is very limited or no resource allocation prior to the information transfer phase
- the bandwidth available for the ABR calls fluctuate in time in accordance with the load on the link [1].

Since we have to dispose of the direct application of the equivalent bandwidth based approach when devising and analyzing link capacity sharing policies, we seek alternative methods to do this. This problem has been raised by for instance in [2] without providing an analytical approach or a modeling framework. While many interesting contributions have proposed link allocation- and associated performance analysis methods for complete sharing, complete partitioning, partial overlap, trunk reservation, class limitation [3] and Markov decision [4], very few proposes efficient computational technique for ATM with CBR[2] and ABR classes, especially when the state space becomes large, say

University of Denmark in Lyngby. The authors wish to thank Gergely Mátéfi his help in the implementation of the proposed method.

[2] Because we model the system on the call level, in the rest of this paper we use the CBR service class as one which represents strict QoS guarantees, with the understanding that by adopting the notion of equivalent bandwidth, this class could as well be the VBR class.

in the order of $10^4 - 10^6$. Thus, our goal is to 1) extend the widely used multi-rate models such that they allow the ABR bandwidth to fluctuate between the minimal and the peak bandwidth during the call's holding time, 2) propose a simple and yet efficient method for link capacity sharing between calls coming from different ATM service classes and 3) devise efficient computational technique for the calculation of the throughput and blocking probabilities, applicable for large systems.

2 The Multi-service Model of an ATM Link

In this Section we formulate the Markovian model of a single ATM transmission link receiving CBR and ABR traffic. In the presentation we restrict ourselves to two CBR classes and a single ABR class, but the model is extendible to more general cases. More traffic classes increase both the complexity and the size of the state space, and the numerical results become more difficult to interpret, and therefore we believe that it is reasonable to start with these restrictions. It should be pointed out, however, that both the basic idea of the model extension to include ABR traffic and the results are applicable to more general cases as well.

The system under consideration consists of an ATM link with capacity C, which is supposed to be an integer number in some suitable bandwidth unit, say $Mbps$. Calls arriving at the link belong to one of the following three traffic classes:

- Narrow-band CBR calls are characterized by their peak bandwidth requirement b_1, call arrival rate λ_1 and departure rate μ_1;
- Wide-band CBR calls are characterized by their peak bandwidth requirement b_2, call arrival rate λ_2 and departure rate μ_2;
- ABR calls characterized by their peak bandwidth requirement b_3, call arrival rate λ_3, minimal bandwidth requirement b_3^{min}, and their *ideal* departure rate μ_3. By ideal we mean that the peak bandwidth is available during the entire duration of the call.

One may think of an ABR class call as one that upon arrival has an associated amount of data to transmit (W) sampled from an exponentially distributed service requirement, with distribution $G(x) = 1 - e^{-\frac{b_3}{\mu_3}x}$, which in the case when the peak bandwidth b_3 is available during the entire duration of the call gives rise to an exponentially distributed service time with mean $1/\mu_3$. Since the free capacity of the link fluctuates in time in accordance with the instantaneous number of CBR and ABR calls in service, the bandwidth given to the ABR calls may drop below the peak bandwidth requirement, in which case the actual holding time of the call increases. All three types of calls arrive according to independent Poisson processes, and the holding time for CBR calls are exponentially distributed. As we will see, the moments of the holding time of the ABR calls can be determined using the theory of Markov reward processes. Three underlying assumptions of the above model are noteworthy. First, we assume that the ABR calls are greedy, in the sense that they always occupy the maximum possible bandwidth on the link, which is the smaller of their peak bandwidth requirement b_3 and the equal share of the bandwidth left for ABR calls by the CBR calls (which will depend on the link allocation policy). Secondly, we assume that all ABR calls in progress share equally the available bandwidth among themselves, i.e. the newly arrived ABR call and the in-progress ABR calls will be squeezed to the same bandwidth unless each of them gets their peak bandwidths. Note that if a newly arriving call decreased the ABR bandwidth below b_3^{min}, that call is not admitted into the system, but it is blocked and lost. Also note, that arriving CBR as well as ABR calls are allowed to "compress" the in-service ABR calls, as long as the minimal bandwidth constraint is kept. Thirdly, the model assumes that the rate control of the ABR calls in progress is ideal, in the sense that an infinitesimal amount of time after any system state change (i.e. call arrival and departure) the ABR sources readjust their current bandwidth on the link.

It is intuitively clear that the residency time of the ABR calls in this system not only depends on the amount of data they want to transmit, but also on the bandwidth they receive during their holding times. In order to specify this relationship we define the following quantities:

- $\theta(t)$ defines the instantaneous *throughput* of the ABR calls at time t (e.g., if there are n_1, n_2, n_3 narrow-band CBR, wide-band CBR, and ABR calls in the system at time t, respectively, the instantaneous throughput is $min(b_3, (C - n_1 b_1 - n_2 b_2)/n_3))$. Note that $\theta(t)$ is a discrete r.v. for any $t \geq 0$.
- $T_x = \inf\{t \mid \int_0^t \theta(\tau) d\tau \geq x\}$ (r.v.) gives the time it takes for the system to transmit x amount of data through an ABR call,
- $\theta_x = x/T_x$ defines the *throughput* of the ABR call during the transmission of x data unit. Note that θ_x is a continuous r.v.
- $\theta = \int_0^\infty \theta_x \, dG(x)$ (r.v.) defines the *throughput* of the ABR call.

In addition, we associate the maximal accepted blocking probabilities with both CBR classes, i.e., B_1^{max} and B_2^{max} respectively and the minimal accepted throughput θ^{min} with the ABR class. We refer to the set of the arrival $(\lambda_1, \lambda_2, \lambda_3)$ and departure rates (μ_1, μ_2, μ_3)[3], the bandwidths (b_1, b_2, b_3) and minimal ABR bandwidth (b_3^{min}), the blocking probability (B_1^{max}, B_2^{max}) and ABR throughput constraints (θ^{min}) as the *input parameters* of the system.

[3] μ_3 is the maximum departure rate of the ABR class assuming that the bandwidth of the ABR connection equals to b_3.

The system under investigation (with the above assumptions on the arrival processes and holding times/transmission requirements) is a Continuous Time Markov Chain (CTMC) whose state is uniquely characterized by the triple $i = (n_1, n_2, n_3)$, where n_1 and n_2 are the number of narrow-band and wide-band CBR calls in the system, respectively, and n_3 is the number of ABR calls in the system. The structure of the CTMC's generator matrix $\mathbf{Q}$ reflects the applied link allocation policy and therefore we first need to define it.

We would like to define the link allocation policy such that it is able to minimize the call blocking probability for the ABR calls while it is able to take into account the GoS (blocking probability) constraints for the CBR calls and the minimal throughput constraint for the ABR calls. Because of its flexibility (in that it is able to take into account the above constraints) and simplicity (in that the performance measures of interest can be determined even for large systems) we adopt the *partial overlap, POL* link allocation policy from the multi-rate circuit switched modeling paradigm [5].

According to the POL policy the link capacity C is divided into two parts, the C_{COM} common part and the C_{ABR} part, which is reserved for the ABR calls only, such that $C = C_{COM} + C_{ABR}$. Under the considered POL policy the number of calls in progress on the link is subject to the following constraints:

$$n_1 \cdot b_1 + n_2 \cdot b_2 \leq C_{COM} \quad (1)$$
$$N_{ABR} \cdot b_3^{min} \leq C_{ABR} \quad (2)$$
$$n_3 \leq N_{ABR} \quad (3)$$

where N_{ABR} stands for the maximum number of ABR calls in the system and will be determined later. Note that this policy has two free parameters, (C_{COM} and N_{ABR}) which allows for the easy dimensioning of a system with blocking and throughput constraints. Furthermore, we find it relatively easy to analyze systems with large state space as well.

The set of such triples which satisfy these constraints constitutes the set of *feasible states* of the system which we denote by $\mathcal{S}$. Cardinality of the state space can be determined with (4).

$$\#\mathcal{S} = (N_{ABR} + 1) \cdot \sum_{i=0}^{\lfloor C_{COM}/b_1 \rfloor} \left\lfloor \frac{C_{COM} - i \cdot b_1}{b_2} + 1 \right\rfloor \quad (4)$$

In (1) the ABR connections are protected from CBR calls. In (2,3) the maximum number of ABR connections is limited by two constraints. (2) protects the CBR calls from ABR connections while (3) protects the ABR connections from the new ABR calls, because if too many ABR connections were admitted into the system then θ could decrease below θ^{min}. Clearly, θ can be modified by changing the value of N_{ABR}.

It is easy to realize that the $\mathbf{Q}$ generator matrix possesses a nice structure, because only transitions between "neighboring states" are allowed in the following sense. Let $q_{i,j}$ denote the transition rate from state i to state j. Then, taking into account the above constraints associated with the proposed POL policy, the non-zero transition rates between the states are:

$$q_{i,i_{k+}} = \lambda_k, \qquad k = 1, 2, 3 \tag{5}$$
$$q_{i,i_{k-}} = n_k \cdot \mu_k, \qquad k = 1, 2 \tag{6}$$
$$q_{i,i_{3-}} = r_i \cdot \mu_3, \tag{7}$$

where $i_{1+} = (n_1 + 1, n_2, n_3)$ when $i = (n_1, n_2, n_3)$; i_{k+} and i_{k-} $(k = 1, 2, 3)$ are defined similarly; and

$$r_i = \min\Big(n_3\ ,\ \frac{C - (b_1 \cdot n_1 + b_2 \cdot n_2)}{b_3}\Big). \tag{8}$$

(5) represents the state transitions due to a call arrival, while (6) and (7) represent the transitions due to call departures. The $r_i b_3$ quantity as defined by (8), denotes the total bandwidth of the ABR connections when the system is in state i. The $\mathbf{Q}$ generator matrix of the CTMC is constructed based on the transition rates defined in (5), (6) and (7). Note that the POL policy as described above is fully determined by specifying its two parameters: the C_{COM} common part, and the N_{ABR} maximal number of ABR calls. We refer to the C_{COM} and the N_{ABR} parameters of the POL policy as the *output parameters* of the system.

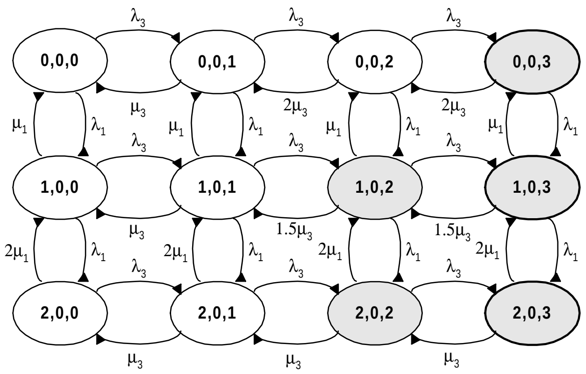

Fig. 1. The state space of the small example when $b_2 = 0$

Now, we consider a small system for illustration purposes. Figure 1 depicts the state space of a system with capacity $C = 4$ and with a CBR and an ABR class (i.e., for ease of presentation $n_2 = 0$ is kept fixed). We let $C_{COM} = 2$, $b_1 = 1$ and $b_3 = 2$. The ABR class is further characterized by its *minimal* accepted bandwidth, which we here let $b_3^{min} = 2/3$. This setting gives rise to 12 feasible states, out which there are 5 (gray) states where the ABR bandwidth is compressed below the peak bandwidth specified by b_3. In for instance state $(1, 0, 3)$ each of the 3 ABR calls receive 1/2 bandwidth, which gives rise to an aggregated ABR death rate $1.5\mu_3$.

It can be seen that the system in Figure 1, as well as the considered system in general, is not reversible, since the local balance equations do not hold due to the possible compression of ABR bandwidth. Hence, the steady state distribution does not obey a product form solution. However, the generator matrix, as we will see next possesses a nice birth-death structure allowing for efficient numerical solution approaches.

As we will see, the POL policy is easy to dimension, and it has two free parameters, with which the performance of the system can be tuned. It guarantees call level GoS for CBR calls and throughput for ABR services. The GoS of CBR calls is guaranteed by the proper setting of C_{COM}. In case of a change in the ABR load (i.e. the call arrival intensity (λ_3) or the parameter of required data to transmit (b_3/μ_3)), the N_{ABR} parameter has to be adjusted to keep the required throughput. We divide the problem of determining the output parameters of the POL policy into two steps. In the first step we determine the minimum required capacity for CBR calls, that guarantees the required blocking probability:

$$\mathbf{min}\Big\{C_{COM} \ : \ B_1 \le B_1^{max} \ , \ B_2 \le B_2^{max}\Big\} \tag{9}$$

where B_1 (B_2) is the blocking probability of the narrow-band (wide-band) CBR class. In the second step we determine the maximum number of ABR calls simultaneously present in the system. In fact, we minimize the blocking probability of the ABR calls (by determining the maximum number of admissible ABR calls) applying constraints on the throughput of the ABR connections. The following two constraints are considered:

- *the average throughput constraint* :

$$\mathbf{max}\Big\{N_{ABR} \ : \ E(\theta) \ge \theta^{min}, \ N_{ABR} \le \frac{C - C_{COM}}{b_3^{min}}\Big\} \tag{10}$$

  i.e., the average throughput of ABR connections can not be less than θ^{min}.
  To make a plausible interpretation of this constraint let us assume that the distribution of θ is fairly symmetric around $E(\theta)$, i.e. the median of θ is close to $E(\theta)$. In this case the probability that an ABR call obtain less bandwidth than θ^{min} is around 0.5. Users (even with ABR traffic) often prefers more informative throughput constraints like the next one.

- *the throughput threshold constraint*:

$$\mathbf{max}\Big\{N_{ABR} \; : \; Pr(\theta_x \leq \theta^{min}) \leq \varepsilon, \; \forall x, \; N_{ABR} \leq \frac{C - C_{COM}}{b_3^{min}}\Big\} \quad (11)$$

  This throughput threshold constraint requires that the throughput of ABR connections is greater than θ^{min} with a predefined probability $(1-\varepsilon)$ independent of the associated service requirements (x). Hence, if the (input) parameter θ^{min} is much less than $E(\theta)$ then this second constraint is much more informative for the user about the expectable minimal level of the ABR throughput.

The call blocking probabilities of the CBR and ABR calls are calculated from the steady state distribution ($\underline{P} = [p_i]$) of the CTMC specified by its generator matrix $\mathbf{Q}$.

3 Analysis of ABR Throughput Measures

Once the steady state distribution of the CTMC has been found, we can determine the required throughput measures the *average throughput* and the *throughput threshold* defined by equations (10) and (11), respectively.

The calculation of the average throughput of the ABR calls is straightforward, since

$$E(\theta) = \frac{\sum\limits_{(n_1,n_2,n_3)\in\mathcal{S}} b_3 \; p_{(n_1,n_2,n_3)} \; r_{(n_1,n_2,n_3)}}{\sum\limits_{(n_1,n_2,n_3)\in\mathcal{S}} n_3 \; p_{(n_1,n_2,n_3)}} \; . \quad (12)$$

Unfortunately, it is much harder to check the throughput threshold constraint in (11), since neither the distribution nor the higher moments of θ_x can be analyzed based on the steady state distribution of the above studied Markov chain. Hence, in this section, a different approach is applied to analyze the system with the throughput threshold constraint.

The constraint in (11) can be analyzed based on the distribution of T_x applying:

$$Pr\left(\theta_x \leq \theta^{min}\right) = Pr\left(\frac{x}{T_x} \leq \theta^{min}\right) = Pr\left(T_x \geq \frac{x}{\theta^{min}}\right) \; . \quad (13)$$

Since it is hard to evalutate the distribution of T_x directly, but there are effective numerical methods to obtain its moments through the Markov Reward

Model [6] that describes the system behaviour during the sojourn of tha tagged ABR call [6]. We check the throughput threshold constraint in (11) based on the moments of T_x applying the Markov inequality which gives the following relations:

- if applied for $T_x^n \geq \frac{x^n}{b_3^n}$:

$$Pr\left(T_x \geq \frac{x}{\theta^{min}}\right) \leq \frac{\dfrac{E(T_x^n)}{x^n} - \dfrac{1}{b_3^n}}{\dfrac{1}{\theta^{min^n}} - \dfrac{1}{b_3^n}} \tag{14}$$

- if applied for $(T_x - E(T_x))^{2n} \geq 0$:

$$Pr\left(T_x \geq \frac{x}{\theta^{min}}\right) \leq \frac{M^{(2n)}(T_x)}{\left(\dfrac{x}{\theta^{min}} - E\left(T_x\right)\right)^{2n}} \tag{15}$$

where $n \in \mathbb{N}$ and $M^{(2n)}(T_x) = E([T_x - E(T_x)]^{2n})$ denotes the $2n$-th central moment of T_x. The inequalities (14)-(15) applied for different n provide different upper bounds for $Pr\left(T_x \geq \frac{x}{\theta^{min}}\right)$. If at least one of the upperbounds of $Pr\left(T_x \geq \frac{x}{\theta^{min}}\right)$ is less than ε for the considered x than the throughput threshold constraint is fulfilled.

The complete link allocation procedure is summarized in Figure 2.

4 Conclusion

An ATM call level model is proposed, which is an extension of the classical multi-rate loss model in that it allows one to model service classes whose bandwidth fluctuates in time in accordance with the instantaneous load on the link. This is achieved by allowing such service classes to specify their minimal accepted bandwidth in addition to their peak bandwidth requirement. Furthermore, this type of calls specify their ideal mean call holding time, which corresponds to the total amount of required service, rather than specifying the mean call holding time.

We have used this model to investigate the performance of the adoption of the Partial Overlap link allocation policy for an ATM transmission link which is offered CBR and ABR calls. By employing efficient numerical methods to find the steady state of the system and the reward measures of a modified system, we have found that the POL policy is relatively easy to dimension and is able to take into account GoS and throughput constraints and to minimize the ABR class blocking probability.

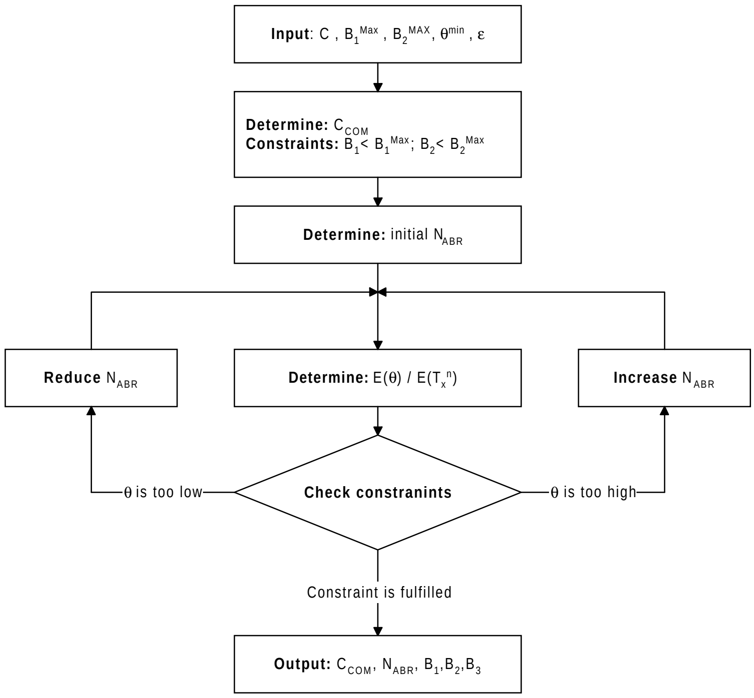

Fig. 2. The block diagramm of the link allocation procedure

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