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Discrete-Time Modeling of the Frame-Based Generic Cell Rate Algorithm

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Abstract

The Guaranteed Frame Rate service recently defined by the ATM Forum allows users to send data in excess of their guaranteed service rate but only guarantees that such traffic will be delivered within the limits of available network resources, that is, it is transported on best effort. In order to distinguish traffic sent in line with the guaranteed service rate from traffic sent in excess, a frame-based version of the Generic Cell Rate Algorithm is employed. This paper presents an analytical approach that forms the basis for dimensioning traffic descriptors related to the Frame-Based Generic Cell Rate Algorithm. The approach is based on a discrete-time analysis technique.

Keywords

Asynchronous Transfer Mode, Best-Effort Service, Guaranteed Frame Rate, Packet-Based Service, Performance Analysis.

1 Introduction

If transporting traffic from traditional data applications — such as the *Transmission Control Protocol* (TCP) — over ATM networks then cell loss becomes a real issue because of packet fragmentation into multiple smaller ATM cells. Even a low cell loss ratio can cause a significant loss rate of higher-layer packets and therefore the goodput of a connection can be much less than the throughput measured in ATM cells delivered. Another issue is the problematic prediction of traffic descriptors since traffic characteristics of data applications are usually very difficult to estimate due to the severe burstiness of the sources.

These problems motivated the introduction of a service category — called *Guaranteed Frame Rate* (GFR) — in which the network provides the user with a minimum service rate guarantee under the assumption of a given maximum packet size. The GFR service allows users to send traffic in excess of their guaranteed service rate but only guarantees that such packets will be delivered within the limits of available resources. That is, they are offered best effort service. Best effort packets will be delivered either completely or be fully discarded in order to increase goodput.

For ATM traffic management, packets sent in line with the guaranteed service rate have to be distinguished from packets sent in excess. Proper cell or packet discarding in congested network elements would be impossible otherwise. This distinction is performed by a frame-based version of the *Generic Cell Rate Algorithm* (GCRA), termed F-GCRA. In contrast to the conventional GCRA employed for peak cell rate and sustainable cell rate monitoring, the F-GCRA determines a whole frame either as eligible for guaranteed service or not, where a frame directly corresponds to a higher-layer packet. Hence, the F-GCRA plays a central role in the GFR service.

This paper is concerned with modeling the F-GCRA with respect to traffic descriptor dimensioning. After reviewing the specification of the GFR service category more detailed in Section 2, the reference algorithm employed by the GFR service is provided in Section 3. Section 4 presents a discrete-time modeling approach that is useful for parameter dimensioning. An extended traffic model is suggested in Section 5 and the paper concludes with a brief summary in Section 6.

2 GFR Service Category

The main motivation behind the introduction of the GFR service is to keep the simplicity of the UBR service while providing the additional feature to reserve some minimum guaranteed service for a connection [1]. In fact, the approach of a minimum service guarantee was also followed with the introduction of the ABR service category. Implementation complexity of adapter cards and network nodes is increased with the ABR service however by a considerable amount due to supporting a rate-based flow control.

Another important factor considered in the definition of the GFR service category is that a large number of today's data applications relies on a packet-based service such as TCP. As already stated in the introduction, for such services the goodput of a connection can be much less than the throughput measured in ATM cells delivered due to packet fragmentation. Hence, in contrast to the VBR.3 service that also allows users to send data in excess of the traffic volume negotiated [6], the GFR service considers the information flow as a flow of frames[†] instead of a flow of cells. Frame boundaries are therefore visible in the network and can be used to selectively discard whole frames. Discarding whole frames avoids transporting useless information since cells can be reassembled to frames — and thus to higher-layer packets — only if the complete data is available. Loosing a single cell of a frame generally causes the rest of the frame data to be useless.

The GFR service is intended to support non-real-time applications and requires user data to be organized in the form of frames that can be delineated by the ATM layer. As specified in [2, 8], it guarantees that if cells conform to a contracted *Peak Cell Rate* (PCR) and frames conform to a contracted *Maximum Frame Size* (MFS) then the frames will receive at least a minimum level of service. Furthermore, frames sent in excess of those which are eligible for guaranteed service are served as network resources allow. Best effort frames will be delivered either completely or be fully discarded.

For indicating excess traffic, the user can send marked frames — by setting the CLP bit in the ATM cell header to one — announcing to the network that such a frame is of lesser importance than an unmarked frame. The minimum service guarantee however only applies to unmarked frames. Additionally, the network is allowed to tag unmarked frames sent in excess if the user has requested the tagging option. Marking or tagging frames that are not eligible for guaranteed service must be accomplished by setting the CLP bit to one in all cells of the frame.

The minimum service guarantee is expressed in terms of a *Minimum Cell Rate* (MCR) for cells in frames that are delivered completely. It is not expressed in terms of a minimum frame rate. This MCR will be honored provided conforming frames arrive in a manner consistent with a leaky bucket algorithm — the F-GCRA — that defines service guarantee eligibility. If frames are available they will be served at a rate at least equal to the MCR, and bursts up to at least a *Maximum Burst Size* (MBS) will be served. The above definition allows a user to expect a minimum service rate when the network is congested while being able to send at higher rates when additional resources are available.

Thus, the F-GCRA is at the heart of the GFR service [7]. It is defined as a frame-based version of the conventional GCRA employed for traffic monitoring and determines service guarantee eligibility for frames sent by the source. Concisely, the F-GCRA is identical to the conventional GCRA except that service guarantee eligibility is determined only by whether or not the first cell of a frame passes the test. All succeeding cells that correspond to the same frame are valued identically.

Applications have to specify appropriate values for the parameters MCR and MBS at connection establishment in order to achieve the minimum service quality required. This dimensioning is not straightforward and application specific, making modeling and performance analysis of the F-GCRA necessary. Before addressing this topic in the Sections 4 and 5 the basic algorithm is presented.

[†] Frames correspond to AAL PDUs that in turn contain complete or partial higher-layer packets.

3 Frame-Based Generic Cell Rate Algorithm

As the conventional GCRA, the $\mathit{F\text{-}GCRA}(I, L)$ defined in [8] is a function of two parameters, the increment parameter I that corresponds to $1/\mathit{MCR}$ and the limit parameter L. The limit parameter is determined by:

$$L \quad = \quad (\mathit{MBS} - 1) \cdot (1/\mathit{MCR} - 1/\mathit{PCR}) \; + \; \mathit{CDVT2}\,, \tag{1}$$

where $\mathit{CDVT2}$ is the cell delay variation tolerance applicable to the MCR. Both parameters are not restricted to integer values. Defining L as given in Equation (1) allows bursts to be served up to the MBS. A discussion on the dimensioning of this parameter is reported in [9].

More explicitly, the continuous-state leaky bucket version of the F-GCRA is described by the pseudo-code shown in Figure 1. The algorithm is invoked for each conforming cell on a connection and has the state variables X, LET (*Last Eligibility Time*), and *Eligible*, where the latter is a boolean variable. Initially, $X = 0$ and $\mathit{LET} = 0$. Note that cell conformance is defined solely with respect to the PCR and the MFS whereas eligibility for guaranteed service is defined by the F-GCRA. The variable X' is a temporary variable of the algorithm.

```
X’ := X - (ta - LET)

if (first cell in frame) then
  if (CLP == 1) or (X’ > L) then
    Eligible := false
  else
    Eligible := true
  endif
endif

if (Eligible) then
  X := max(0, X’) + I
  LET := ta
endif
```

Figure 1: *The Frame-Based Generic Cell Rate Algorithm*

Upon the arrival of a cell at time t_a at a given interface along the ATM connection the value of the temporary variable X' is computed. It denotes the virtual burst length at time t_a. If the cell is the first cell of a frame then the algorithm determines whether the frame is eligible for service or not. This is done by checking the CLP bit and comparing X' to L. The minimum service guarantee does not apply to frames having their CLP bit set to one. Afterwards, the state variable X is updated and the LET is set to the current time for all cells belonging to frames that are eligible for guaranteed service.

The F-GCRA described above ignores the issue of non-conforming frames, that is, frames whose cells do not conform to the PCR or whose length exceeds the MFS. A number of variants may be defined with regard to the handling of non-conforming frames. This issue is not addressed in this paper.

4 Modeling and Performance Evaluation

In the following, a traffic model of the F-GCRA and its analysis is presented. Using the approach the traffic descriptors MCR and MBS can be dimensioned with respect to a given source behavior and the service guarantee required. Dimensioning examples are provided at the end of this section.

4.1 Traffic Model

The GFR service is intended mainly for non-real-time applications that utilize ATM networks for transporting higher-layer packets of a size considerably larger than the ATM cell payload. The traffic pattern typically observed with such sources — for example TCP applications — can be described by the class of on/off-processes. On-states correspond to periods where a single packet is transmitted whereas off-states represent intervals where no data is available for transmission.

An example scenario of the on/off-process type considered in this paper is depicted in Figure 2. During on-states, cells arrive in fixed intervals. The time elapsing between two consecutive cell arrivals is denoted by d. It is expressed in the number of ATM cell slots and corresponds directly to 1/PCR. We assume that all on-states start with a cell arrival. The end of on-states is not synchronized to the arrival pattern, cf. Figure 2. Intuitively, no cell arrivals occur during off-states.

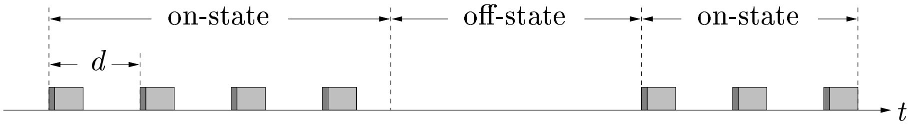

Figure 2: *On/off source model*

The lengths of the on- and off-states are assumed to be independent of each other and follow general distributions. For the sake of generality, the distribution describing the lengths of the on-states can differ from that describing the lengths of the off-states. However, both are assumed to be discrete distributions. The motivation for restricting the state length description to discrete distributions stems from the slotted nature of ATM cell streams.

The F-GCRA is investigated based on this specific source model and the traffic model depicted in Figure 3. Since we are primarily focusing on the eligibility of frames all cells are assumed to be conforming, that is, they conform to the PCR and the frame lengths

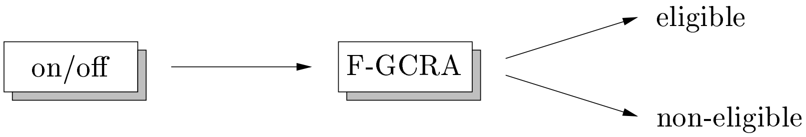

Figure 3: *F-GCRA traffic model*

do not exceed the MFS. A frame in the sense of the GFR service is set equal to the cells generated during an on-state in order to determine whether a cell is eligible for guaranteed service or sent in excess. Thus, the first cell arrival in each on-state determines whether the succeeding cells of this state are eligible for service or not.

The ratio of excess traffic — it directly corresponds to the ratio of non-eligible frames and cells, respectively — can be determined when solving this model. System parameters are the inter-cell distance and the distributions characterizing the on/off-process as well as the increment and limit parameter defining the F-GCRA.

4.2 System State Evolution

Before outlining the analysis of the traffic model we first take a closer look at the system state evolution of the F-GCRA. The system state is sufficiently described by the state variable X. It denotes the virtual burst length, cf. Section 3. Considering the on/off-process, a sample path of this variable is shown in Figure 4. At each arrival of a cell belonging to a frame that is eligible for guaranteed service the system state X is increased by the increment I. Between cell arrivals X is decreased by one for each slot.

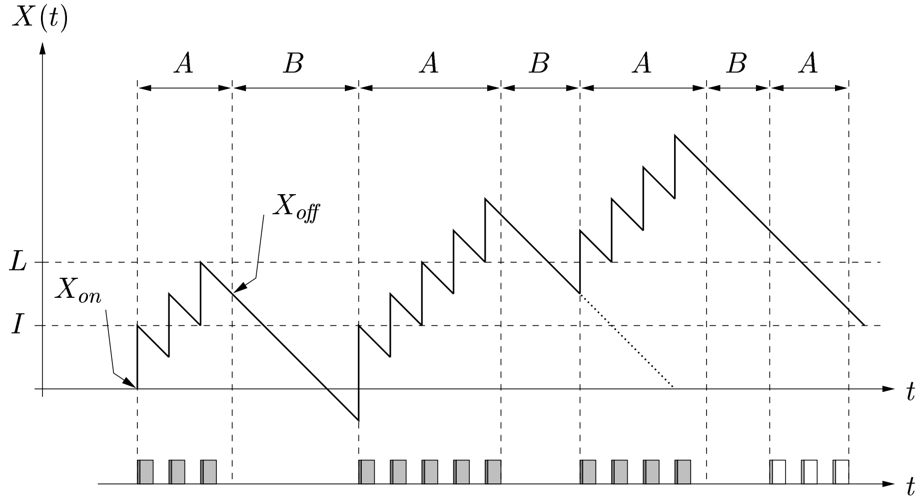

Figure 4: *Sample path of the state variable X*

Figure 4 shows a scenario with four frames. The first three frames are eligible for service since the value of X observed at the beginning of the frame is lower than the limit L. In contrast, the last frame is identified to be sent in excess of the traffic volume due to a virtual burst length X that is larger than L at the time the first cell arrives.

We introduce a number of random variables considered in the analysis. The lengths of the on- and off-states is denoted by the variables A and B, respectively. The system state just before the beginning of on-states is described by X_{on}. A frame is therefore identified as eligible for service if $X_{on} < L$. In the same manner, the random variable X_{off} describes the system state just before the beginning of off-states. Figure 4 indicates these variables exemplary for the first on-state and the succeeding off-state.

The analysis presented in the following is of an iterative nature and operates in the discrete-time domain. Using the random variables introduced above, the variable X_{on} is related to X_{off} and vice versa. A description of the steady-state system behavior is obtained by iteratively computing the corresponding probability mass functions until convergence is reached. The system performance is completely expressed by the mass function of X_{on} since eligibility is determined according to the first cell arrival in a frame.

A similar approach is used in [3] to analyze the conventional GCRA if on/off-traffic is monitored. Instead of considering only instants at the beginning of on- and off-states, the analysis presented in [3] determines the system state distributions before each cell arrival. This more detailed observation of the system state process is required since the conventional GCRA individually decides for each cell whether it conforms to the traffic descriptors or not.

4.3 Discrete-Time Analysis

In the following, the system state X is assumed to be an integer variable. Therefore, the approach is of an exact nature only if the increase parameter I is an integer. For non-integer values we obtain approximate results. The choice of the limit parameter L has no influence on the exactness of the approach.

We start with modeling the off-states. During off-states cell arrivals do not occur and therefore the system state X decreases by one for each cell slot. Consequently, the random variable X_{on} denoting the system state just before the next frame arrival is obtained by:

$$X_{on} \quad = \quad \max\{0,\, X_{off} - B\}\ . \tag{2}$$

In terms of probability mass functions, Equation (2) is expressed by:

$$x_{on}(i) \quad = \quad \pi_0[\, x_{off}(i) \,\star\, b(-i)\,]\ , \tag{3}$$

where $x_{on}(i)$, $x_{off}(i)$, and $b(i)$ represent the mass functions corresponding to X_{on}, X_{off}, and B, respectively. The operator '$\star$' denotes the discrete convolution operation and the projection $\pi_0[\cdot]$ is defined as:

$$\pi_0[z(i)] \quad = \quad \begin{cases} 0 & : \; i < 0 \\ \sum\limits_{j=-\infty}^{0} z(j) & : \; i = 0 \\ z(i) & : \; i > 0 \end{cases} \ . \tag{4}$$

It models the restriction of the system state X to non-negative values, that is, the maximum function used in the third from last line in the pseudo-code, cf. Figure 1.

On-states are modeled in a similar manner. The system state is increased by a certain amount if the frame is identified as eligible for guaranteed service, depending on the length of the state. Note, the number of cells arriving is a function of the state length. Considering that the system state is decreased by one for each cell slot yields the relation:

$$X_{\mathit{off}} = \begin{cases} X_{on} + \lceil A/d \rceil \, I - A & : \quad X_{on} < L \\ \max\{0, \, X_{on} - A\} & : \quad X_{on} \geq L \end{cases} \quad . \tag{5}$$

This relation can not be described by a single equation in terms of probability mass functions. The description is therefore split in two steps. First, the probability mass functions $x_{on}^{k}(i)$ are determined. They denote the system state at the end of an on-state of length k and are computed as:

$$\begin{aligned} x_{on}^{k}(i) &= \pi_0[\, \sigma_L[\, x_{on}(i) \, \star \, \delta\,(i - \lceil k/d \rceil \, I + k)\,] \quad + \\ &\qquad \sigma^L[\, x_{on}(i) \, \star \, \delta\,(i + k)\,]\,] \, . \end{aligned} \tag{6}$$

The operators $\sigma_m[\cdot]$ and $\sigma^m[\cdot]$ truncate the mass functions in order to model the cases of service eligibility and non-eligibility separately. They are defined as:

$$\sigma_m[z(i)] = \begin{cases} z(i) & : \quad i < m \\ 0 & : \quad i \geq m \end{cases} \tag{7}$$

and

$$\sigma^m[z(i)] = \begin{cases} 0 & : \quad i < m \\ z(i) & : \quad i \geq m \end{cases} \quad . \tag{8}$$

The Kronecker Delta $\delta(\cdot)$ is defined by $\delta(i) = 1$ for $i = 0$, else $\delta(i) = 0$.

Weighting the conditional probability mass functions $x_{on}^{k}(i)$ according to the distribution that describes the lengths of the on-states — it is denoted by the function $a(i)$ — yields the mass function of the random variable X_{off}:

$$x_{\mathit{off}}(i) = \sum_{k=0}^{\infty} a(k) \cdot x_{on}^{k}(i) \, . \tag{9}$$

Finally, we obtain a description of the system state in equilibrium by calculating the Equations (3), (6), and (9) iteratively until convergence is reached.

The ratio of frames eligible for guaranteed service is derived from the probability mass function $x_{on}(i)$. Since frames are identified to be eligible if $X_{on} < L$ the following equation computes the probability p_e that a frame is sent in line with the MCR:

$$p_e = \sum_{i=0}^{L-1} x_{on}(i) \, . \tag{10}$$

Consequently, frames that are not eligible for service are observed with probability p_{ne}:

$$p_{ne} = 1 - p_e \, . \tag{11}$$

Note that the same probabilities are observed if considering individual cells instead of whole frames. The reason for this equality is that the F-GCRA identifies frames to be eligible either completely or not at all.

4.4 Dimensioning Examples

The first two system parameters we look at are the limit parameter L and the PCR. Note that the latter corresponds to the distance d between two consecutive cell arrivals during on-states. Figure 5 shows the ratio of excess traffic as a function of the limit parameter L for three different choices of d. The distributions describing the on- and off-state lengths are assumed to be geometric and the MCR is set to 20 per cent of the link rate, that is, $I = 5$. In the case of the on-states, the distribution is shifted by two. The shifting is motivated by the fact that the length of a frame corresponds to at least one cell plus the cell that marks the frame boundary at the end. For $d = 1$ the expectations of the on- and off-state lengths are set to 10 and 30 slots, respectively. Both values are adjusted if considering $d = 2$ and $d = 3$ in order to achieve the same system load of 25 per cent.

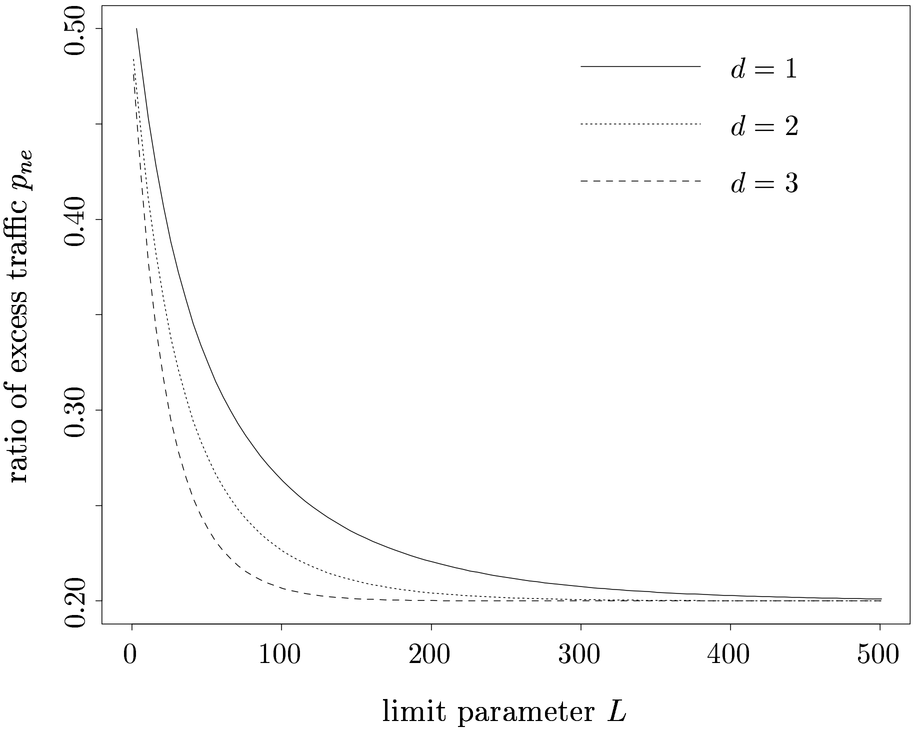

Figure 5: *Influence of PCR reduction*

As expected, the ratio of excess traffic decreases with increasing values of L and converges to 20 per cent. The convergence is faster for larger values of d, which is explained by the smoother arrival process. In general, PCR reduction allows to decrease the ratio of excess traffic up to a certain extent. It is however paid by increasing delays as typical for traffic shaping. Setting $d = 4$ would result in on-states of infinite lengths and therefore in a deterministic arrival pattern. Consequently, the ratio of excess traffic would be 20 per cent even if $L = 0$.

In order to eliminate the dependence on the PCR, the limit parameter L is determined as a function of the MBS, cf. Equation (1). Table 1 shows the excess traffic ratio when applying this function to four different choices of the MBS. We observe a reasonable agreement that becomes closer if the MBS increases. An exact adaptation is neither feasible nor required

	$d = 1$	$d = 2$	$d = 3$
MBS	**excess traffic**		
25	0.268	0.248	0.243
50	0.222	0.211	0.208
75	0.208	0.203	0.201
100	0.203	0.202	0.200

Table 1: *Quality of limit parameter adaptation*

for practical purposes since the excess traffic ratio is influenced by the on/off-process type, which typically is unknown at the time of connection establishment.

This dependence is demonstrated by studying the impact of the variability of the state length distributions. For computing the results depicted in Figure 6, negative-binomial distributions have been used for describing the on/off-process. They allow to vary the coefficient of variation c almost independently of the expectation. The other system parameters are set as in the first example for $d = 1$. Figure 6 clearly shows that more excess traffic is detected for larger values of the coefficient of variation c although the total system load is constant and equal to 25 per cent for each of the curves. In fact, the curves depicted in Figure 6 converge with an increasing MBS to the same limit. Due to the strong influence of the on/off-process type on the excess traffic ratio, Equation (1) is considered as sufficiently accurate for practical purposes.

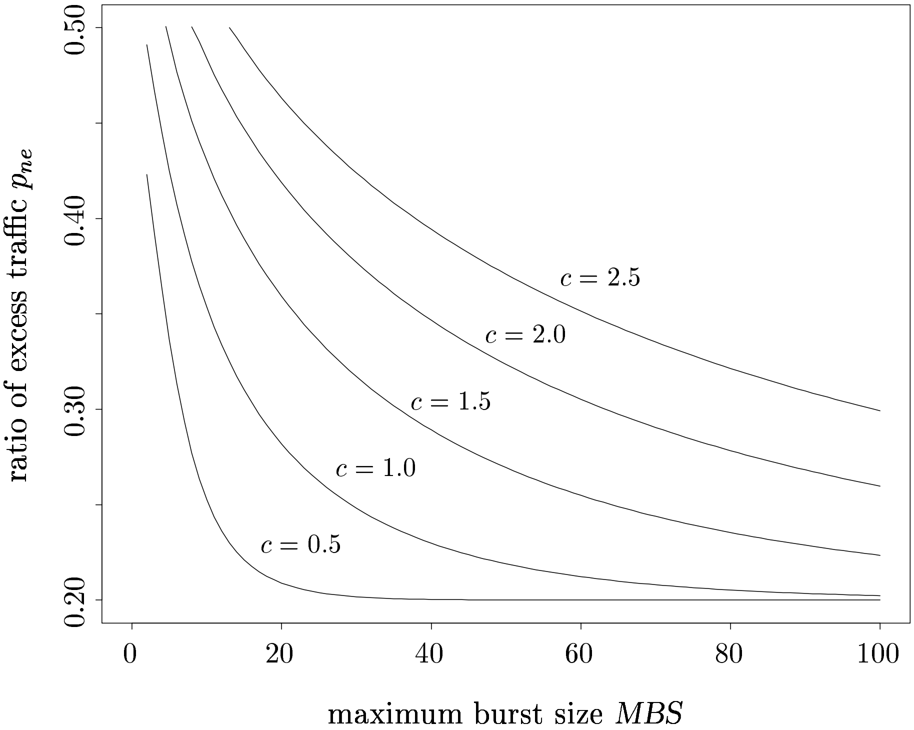

Figure 6: *Impact of on/off-process type on excess traffic volume*

Our third dimensioning example addresses the accurateness of the analytical approach for non-integer values of the increase parameter I. Figure 7 shows the excess traffic ratio as a function of the MCR that directly determines the value of I. The dotted line corresponds to the parameter set described at the beginning of this section while the solid line corresponds to a scenario where the expectations of the on- and off-state lengths are halved. We observe clear changes in the excess traffic ratio at values of the MCR where the computation is exact — that is, $MCR = 0.5, 0.\bar{3}, 0.25, \ldots$ — and at the reciprocal values of $2.5, 3.5, 4.5, \ldots$. The changes result from the error introduced in the computation of the system state at the end of the on-states due to truncating non-integer values into integer numbers. The changes become clearer for shorter durations of on-states, which is explained by a larger relative error in such cases. For dimensioning purposes, regression methods can be used to avoid this effect.

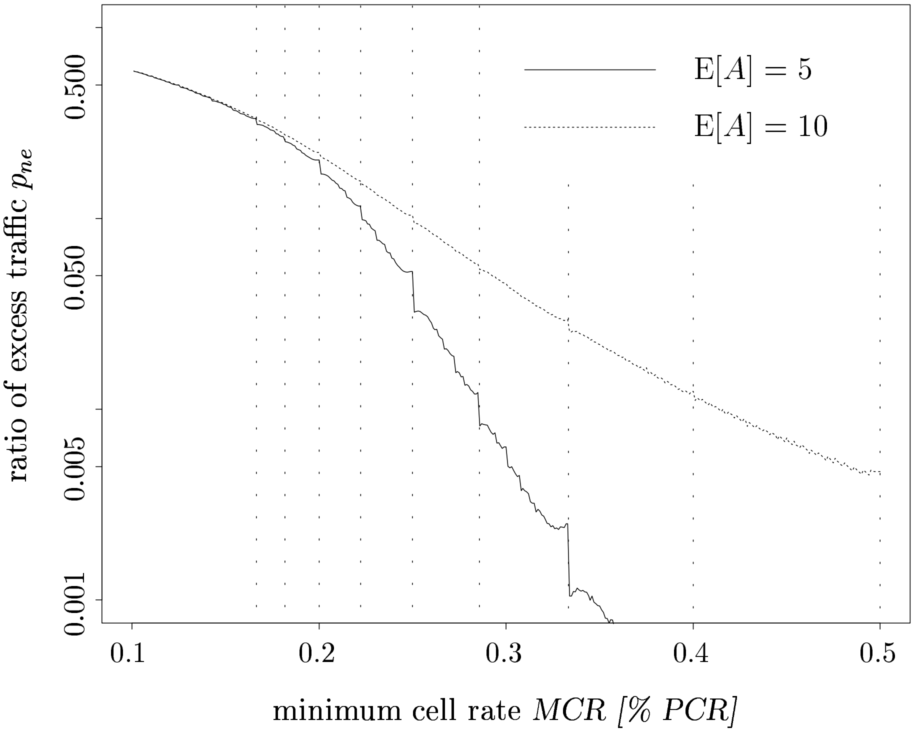

Figure 7: *Approximation accuracy for non-integer parameter values*

5 Further Research

The traffic model and its solution presented in the preceding section allows to determine the ratio of excess traffic for cell streams modeled by an on/off-process. An additional important performance measure for selecting appropriate values of the MCR is the queuing performance. A certain ratio of excess traffic will be discarded in queuing points depending on the choice of the MCR and the current network load. Such effects can not be studied utilizing the simple model discussed above. However, the model together with the analytical approach can be extended to a two-stage traffic model that allows to investigate this dimensioning problem.

Figure 8 shows the basic structure of the extended model. After the cell stream has passed the F-GCRA and cells are marked eligible or non-eligible for guaranteed service, it is offered to a single-server queue. The speed of the server has generally to be dimensioned larger than the MCR since this rate is guaranteed by the network. Additional capacity is used to serve excess traffic, where in the case of buffer overflow different discarding policies are possible, cf. [1]. Thus, the queuing performance can be studied with respect to MCR dimensioning.

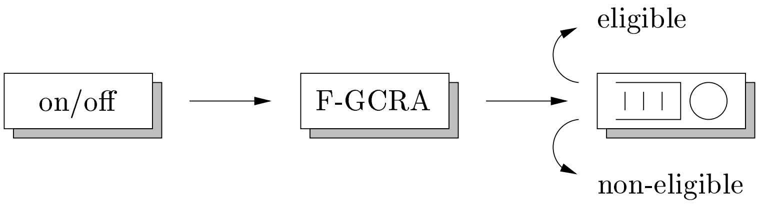

Figure 8: *Extended traffic model for studying queuing performance*

In contrast to the model discussed in Section 4, the system state of the extended traffic model is described by two random variables — the state of the F-GCRA and the state of the single-server queue. The latter is a function of the first. Thus, the analysis approach has also to be extended.

First steps into this directions are reported in [4] and [5]. The papers present an extended version of the discrete-time analysis technique used in this paper, which operates on a two-dimensional state space. Each dimension corresponds to the state of a queuing system or virtual queuing system, where at cell arrivals the updating of the system state is performed with respect to the current state of both queues. Unfortunately, the technique requires that both servers are synchronized and have identical service times.

This problem can be solved by calculating the system state approximately as done in this paper for non-integer values of the increase parameter I, cf. Equations (5) and (6). Until the time of writing, the impact of such an approximate calculation on the accuracy of the final results is however not clear. Details and numerical examples showing the approximation accuracy will be reported in a follow-on paper.

6 Summary

The GFR service recently defined by the ATM Forum uses a frame based version of the GCRA to differentiate frames that are eligible for guaranteed service from frames sent in excess of a minimum service rate. In this paper, a discrete-time analysis of the F-GCRA monitoring on/off-traffic is presented. It forms the basis for dimensioning traffic descriptors related to the F-GCRA. They include the minimum service rate requested from the network and the burst size allowed at maximum. Dimensioning examples have shown that the on/off-process type has a strong influence on the percentage of traffic identified as sent in excess of the guaranteed rate. An extended traffic model was suggested for studying the impact of spare bandwidth on the queuing performance with respect to the choice of the guaranteed service rate.

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