Packet multiplexers with adversarial regulated traffic

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Abstract

We consider a finite-buffer packet multiplexer to which traffic arrives from several independent sources. The traffic from each of the sources is regulated, i.e. the amount of traffic that can enter the multiplexer is constrained by known regulator constraints. The regulator constraints depend on the source and are more general than those resulting from cascaded leaky buckets. We assume that the traffic is adversarial to the extent permitted by the regulators. For lossless multiplexing, we show that if the original multiplexer is lossless it is possible to allocate bandwidth and buffer to the sources so that the resulting segregated systems are lossless. For lossy multiplexing, we use our results for lossless multiplexing to estimate the loss probability of the multiplexer. Our estimate involves transforming the original system into two independent resource systems, and using adversarial sources for the two independent resources to obtain a bound on the loss probability of the transformed system. We show that the adversarial sources are not extremal on-off sources, even when the regulator consists of a peak rate controller in series with a leaky bucket. We explicitly characterize the form of the adversarial source for the transformed problem. We also provide numerical results for the case of the simple regulator. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Consider a finite-buffer packet multiplexer to which traffic arrives from several independent sources. For the multiplexer to provide quality of service (QoS) guarantees, such as limits on packet loss probabilities, it must have some knowledge about the traffic characteristics of the sources. Because the reliability of statistical models of traffic is questionable for many source types, in recent years there have been several studies on the performance of packet-switched nodes that multiplex regulated traffic, e.g. traffic which conforms to known constraints imposed by leaky buckets. These studies suggest that the traffic from the sources is adversarial to the extent permitted by the regulators [1–14,16,19–21,23–27]. Some of these studies assume that the multiplexer provides deterministic QoS guarantees (e.g. no packet loss) whereas others assume that multiplexer provides less stringent probabilistic QoS guarantees (e.g. a limit on the packet loss probability).

In a recent paper, LoPresti et al. [16] examine a packet-switched node with regulated traffic. Motivated by earlier work of Elwalid et al. [9], LoPresti et al. consider both deterministic QoS guarantees and probabilistic QoS guarantees. They assume that each source is regulated by a simple regulator; namely, a regulator that consists of a peak-rate controller in series with a leaky bucket. For deterministic QoS, LoPresti et al. show that if the multiplexer has sufficient link bandwidth and buffer capacity to provide lossless multiplexing, then the multiplexer’s buffer and bandwidth can be allocated among the sources so that the resulting segregated systems are lossless. For probabilistic QoS, they develop a new approach to estimate the loss probability. Specifically, they transform the two-resource (bandwidth and buffer) allocation problem into two independent single-resource allocation problems; they then analyze these simpler, independent resource problems, taking on-off periodic sources for their adversarial sources.

Although the simple regulator is a popular policing mechanism within several standards bodies, it has been observed that it is often a poor characterization of a source’s
worst-case traffic. A tighter and more powerful characterization is given by a more general regulator consisting of a cascade of multiple leaky buckets [10,15,25]. For example, when the sources are VBR video sources, it is often possible to admit significantly more connections by replacing the simple regulator with cascaded-leaky-bucket regulators [25]. It is therefore desirable to extend the important work of LoPresti et al. [16] and Elwalid et al. [9] to the case of more general regulators.

In this paper, we reexamine the model of LoPresti et al. [16] in the context of generalized regulators, which are even more general than cascaded leaky buckets. We first reexamine the lossless multiplexer of LoPresti et al., and extend their lossless results to generalized regulators. Using elementary tools from calculus, we show that if the original multiplexer is lossless, then it is possible to allocate bandwidth and buffer to the sources so that the resulting segregated systems are also lossless. We determine the optimal resource allocations and show that the buffer-bandwidth tradeoff curve is convex for generalized regulators. We also show that the segregation result does not necessarily hold for the delay-based QoS metric, even when the regulators are the simple regulators.

We then examine the multiplexer for probabilistic loss guarantees. We use our results for lossless multiplexing to estimate the loss probability of the multiplexer. As in Ref. [16], our estimate involves the following three steps: (i) choose a point on the buffer-bandwidth tradeoff curve and transform the original system into two independent resource systems; (ii) use adversarial sources for the two independent resources to obtain a bound on the loss probability of the transformed system; and (iii) minimize the bound by searching over all points on the buffer-bandwidth tradeoff curve. Our principle contribution for probabilistic loss guarantees is an explicit characterization of the adversarial source for the transformed problem in Step (ii). Importantly, the most adversarial source is not a periodic on–off source for the transformed problem consisting of two independent resources. In fact, even in the case of simple regulated sources as studied in Ref. [16], the most adversarial source is not a periodic on–off source. Thus, in addition to generalizing the theory in Ref. [16] to the case of general regulated sources, we provide the true adversarial source for the case of the simple regulator. We also provide an algorithm to calculate the estimate of the loss probability, assuming the truly adversarial sources.

We mention here that in Ref. [9] the original multiplexer problem is transformed into a bufferless multiplexer problem, and then the loss probability is bounded with the Chernoff bound. In this case, the worst-case adversarial sources are indeed on–off periodic sources. But when the original problem is transformed into a problem consisting of two independent resources, one bufferless resource and one buffered resource, the worst-case sources are no longer on–off periodic sources, even for simple regulators.

This paper is organized as follows. In Section 2, we define the model and the generalized regulators. In Section 3, we address lossless multiplexing. In Section 4, we address lossy multiplexing. In Section 5, we provide numerical results for lossy multiplexing of simple regulators, i.e. regulators consisting of a peak rate controller in series with a leaky bucket. We summarize our contributions in Section 6.

2. Regulated traffic

We consider a link of rate C which is preceded by a finite buffer of capacity B. Let J be the number of sources that send traffic to the buffer, and let j = 1,...,J index the sources. Each source j has an associated regulator function, denoted by ϵj(t), t ≥ 0. The regulator function constrains the amount of traffic that the jth source can send over an time interval of length t to ϵj(t). More explicitly, if A_j(t) is the amount of traffic that the jth source sends to the buffer over the interval [0, t], then A_j(·) is required to satisfy

A_j(t + τ) - A_j(τ) ≤ ϵ_j(t) for all τ ≥ 0, t ≥ 0.

Fig. 1 shows a multiplexer consisting of a link of rate C, a buffer of capacity B, and J sources with regulator functions, ϵ_j(t), j = 1,...,J.

A popular regulator is the simple regulator, which consists of a peak-rate controller in series with a leaky bucket; for the simple regulator, the regulator function takes the following form:

ϵ_j(t) = min\{ρ_j^1 t, ρ_j^2 t + ρ_j^3 t\}.

For a given source type, the bound on the traffic provided by the simple regulator may be loose and lead to overly conservative admission control decisions. For many source types (e.g. for VBR video [25]), it is possible to get a tighter bound on the traffic and dramatically increase the admission region. In particular, piece-wise linear regulator functions of the form

ϵ_j(t) = min\{ρ_j^1 t, ρ_j^2 t, ..., ρ_j^L t\}

are easily implemented with cascaded leaky buckets [1,5] and can lead to improved admission regions [25].

In this paper, we shall consider extremely general regulator functions, which include as special cases the forms mentioned above. To avoid certain trivialities, however, we shall always assume that ϵ_j(0) = 0, ϵ_j(t) is non-decreasing.
in \( t \), and that \( \epsilon_j(t) \) is subadditive in \( t \) (i.e. \( \epsilon_j(t_1 + t_2) \leq \epsilon_j(t_1) + \epsilon_j(t_2) \) for all \( t_1 \) and \( t_2 \)). Also, unless explicitly mentioned otherwise, we shall assume that each \( \epsilon_j(t) \) is concave in \( t \). Let

\[
\epsilon(t) = \sum_{j=1}^{J} \epsilon_j(t)
\]

be the aggregate regulator function. Due to the concavity of the \( \epsilon_j(t)'s\), the aggregate regulator function \( \epsilon(t) \) is also concave.

Before proceeding with our analysis of the lossless systems, it is convenient at this point to introduce some notation and state a few technical facts. Let \( \epsilon_j^+(t) \) denote the right derivative for \( \epsilon_j(t) \) and \( \epsilon_j^-(t) \) denote the left derivative for \( \epsilon_j(t) \). Let \( \epsilon_j'(t) \) denote the derivative of \( \epsilon_j(t) \) whenever the derivative exists at \( t \). Similarly define \( \epsilon'(t) \), \( \epsilon^-(t) \) and \( \epsilon(t) \). We will make use of the following fact: If \( \epsilon(t) \) is differentiable at \( t' \), then all of the \( \epsilon_j(t)'s \) are differentiable at \( t' \) (due to the concavity of the \( \epsilon_j(t)'s\).

### 3. Guaranteed lossless service and optimal segregation

It is well known [4] that the amount of traffic in the buffer does not exceed \( B_{\text{min}} \), where

\[
B_{\text{min}} = \max_{t \geq 0} \{ \epsilon(t) - Ct \}. \tag{1}
\]

(To avoid trivialities we assume that the maximum is attained in Eq. (1.).) Furthermore, due to sub-additivity, it is possible to define traffic functions \( A_j(t), j = 1, \ldots, J \), such that the buffer contents will attain \( B_{\text{min}} \). Thus the minimum buffer size that will guarantee lossless operation is \( B_{\text{min}} \). Throughout the remainder of this section we assume that the multiplexer is lossless, i.e. we assume that the multiplexer buffer \( B \) satisfies \( B \geq B_{\text{min}} \). It will be useful to write Eq. (1) in a more convenient form. If \( \epsilon(t) \) is differentiable then from Eq. (1) we have

\[
B_{\text{min}} = \epsilon(t_{\text{max}}) - Ct_{\text{max}}, \tag{2}
\]

where \( t_{\text{max}} \) is any solution to \( \epsilon'(t) = C \). More generally, there exists a \( t_{\text{max}} \) such that

\[
\epsilon^+(t_{\text{max}}) \leq C \leq \epsilon^-(t_{\text{max}}), \tag{3}
\]

and any \( t_{\text{max}} \) which satisfies Eq. (2) and also satisfies Eq. (3). Throughout the remainder of this section, fix a \( t_{\text{max}} \) that satisfies Eq. (3) (and therefore Eq. (2) as well).

We now address the following question: Is it possible to allocate bandwidth and buffer to the \( J \) sources so that each of the resulting segregated systems is also lossless? We shall see that the answer to this question is yes, but depends critically on the concavity of the \( \epsilon_j(t)'s\).

To address this issue, consider a new system which consists of a link of rate \( c \) preceded by a finite buffer. Suppose only the traffic from source \( j \) is sent to this system. The minimum buffer size that will ensure lossless operation is

\[
B_{\text{min}}(j, c) = \max_{t \geq 0} \{ \epsilon_j(t) - ct \}. \tag{4}
\]

We say that a collection of \( J \) positive numbers \( c_1, \ldots, c_J \) is a bandwidth allocation if \( c_1 + \cdots + c_J = C \). For a given bandwidth allocation, we create \( J \) segregated systems, with the \( j \)th segregated system having link rate \( c_j \) and receiving traffic only from source \( j \).

#### Theorem 1.

1. For all allocations we may have \( B_{\text{min}} \leq \sum_{j=1}^{J} B_{\text{min}}(j, c_j) \).
2. If one or more of the \( \epsilon_j(t)'s \) is not concave then we may have \( B_{\text{min}} \leq \sum_{j=1}^{J} B_{\text{min}}(j, c_j) \) for all allocations \( c_1, \ldots, c_J \).
3. If each \( \epsilon_j(t) \) is concave then \( B_{\text{min}} = \sum_{j=1}^{J} B_{\text{min}}(j, c_j) \) where \( c_j^* = \epsilon_j(t_{\text{max}}) \) if \( \epsilon(t) \) is differentiable at \( t = t_{\text{max}} \) and where

\[
c_j^* = \epsilon_j^+(t_{\text{max}}) + \alpha(\epsilon_j^-(t_{\text{max}}) - \epsilon_j^+(t_{\text{max}}))
\]

with

\[
\alpha = \frac{C - \epsilon^+(t_{\text{max}})}{\epsilon^-(t_{\text{max}}) - \epsilon^+(t_{\text{max}})}
\]

if \( \epsilon(t) \) is non-differentiable at \( t = t_{\text{max}} \).

#### Proof.

The proof of the first claim follows from Eqs. (1) and (4):

\[
B_{\text{min}} = \max_{t \geq 0} \{ \epsilon(t) - Ct \} = \max_{t \geq 0} \sum_{j=1}^{J} \{ \epsilon_j(t) - c_j t \}
\]

\[
= \sum_{j=1}^{J} \max_{t \geq 0} \{ \epsilon_j(t) - c_j t \} = \sum_{j=1}^{J} B_{\text{min}}(j, c_j)
\]

For the second claim, we offer the following counter-example with \( J = 2, C = 1 \). The envelope function for the first source is:

\[
\epsilon_1(t) = \begin{cases} 
  t & \text{if } 0 \leq t \leq 1, \\
  1 & \text{if } 1 \leq t \leq 3, \\
  1 + (t - 3) & \text{if } 3 \leq t \leq 4, \\
  2 & \text{if } t \geq 4.
\end{cases}
\]

The envelope function for the second source is:

\[
\epsilon_2(t) = \begin{cases} 
  2t & \text{if } 0 \leq t \leq 2, \\
  4 & \text{if } t \geq 2.
\end{cases}
\]

It is easily seen that \( B_{\text{min}} = 3 \) whereas \( B_{\text{min}}(1, c_1) + B_{\text{min}}(2, c_2) \geq 10/3 \) for all allocations. Note that both \( \epsilon_1(t) \) and \( \epsilon_2(t) \) are not concave.
and $\epsilon_j(t)$ are non-decreasing and sub-additive. However, $\epsilon_j(t)$ is not concave.

For the third claim, we first show that $c^*_j = \cdots = c^*_j = C$. Suppose that $\epsilon(t)$ is differentiable at $t_{\text{max}}$. Due to the concavity assumption, this implies that each of the $\epsilon_j(t)$’s is differentiable at $t_{\text{max}}$. Thus

$$\sum_{j=1}^{J} c^*_j = \sum_{j=1}^{J} \epsilon_j(t_{\text{max}}) = \epsilon'(t_{\text{max}}) = C.$$

If $\epsilon(t)$ is not differentiable at $t = t_{\text{max}}$, then it is easy to show directly from the definition of the $c^*_j$’s that $c^*_1 + \cdots + c^*_j = C$. It remains to show that $B_{\text{min}} = \sum_{j=1}^{J} B_{\text{min}}(j, c^*_j)$. For a fixed transmission rate $c$, the concavity of the $\epsilon_j(t)$’s and Eq. (4) imply

$$B_{\text{min}}(j, c) = \epsilon_j(t^*) - ct^*,$$

where $t^*$ is any $t$ that satisfies

$$\epsilon_j(t) \leq c \leq \epsilon_j(t^*). \quad (5)$$

By the definition of $c^*_j$,

$$\epsilon_j(t_{\text{max}}) \leq c^*_j \leq \epsilon_j(t_{\text{max}}).$$

Thus, $t_{\text{max}}$ is a $t$ that satisfies Eq. (5) for $c = c^*_j$. Therefore,

$$B_{\text{min}}(j, c^*_j) = \epsilon_j(t_{\text{max}}) - c^*_j t_{\text{max}},$$

which in turn implies

$$\sum_{j=1}^{J} B_{\text{min}}(j, c^*_j) = \sum_{j=1}^{J} [\epsilon_j(t_{\text{max}}) - c^*_j t_{\text{max}}] = \epsilon(t_{\text{max}}) - C t_{\text{max}} = B_{\text{min}}.$$

From Theorem 1 we know that it is possible to allocate bandwidth and buffer so that the resulting segregated systems are lossless, provided that the regulator functions are concave. This result generalizes a result in Ref. [16], in which all regulators were assumed to be simple regulators. This result also provides a motivation for the approach we take in Section 4 when we study probabilistic QoS.

Theorem 1 also gives fairly explicit formulas for these optimal allocations. In Section 3.1, we outline an efficient algorithm for calculating the allocations.

3.1. Algorithm to calculate allocations

In this section, suppose that each of the regulator functions takes the form of cascaded leaky buckets:

$$\epsilon_j(t) = \min\{t^j_1, \sigma^2_j t, \sigma^3_j t, \ldots, \sigma^l_j t\}.$$

Without loss of generality, we may assume that

$$0 = \sigma^1_j < \sigma^2_j < \cdots < \sigma^l_j,$$

and

$$\rho_j^1 > \rho_j^2 > \cdots > \rho_j^l. \quad (6)$$

Let

$$T_j^l = \frac{\sigma_j^{l+1} - \sigma_j^l}{\rho_j^l - \rho_j^{l+1}}, \quad l = 1, 2, \ldots, L_j - 1.$$

In order to avoid trivialities, we assume that

$$T_j^1 < T_j^2 < \cdots < T_j^{L_j - 1}.$$

With these assumptions, $T_j^1 < T_j^2 < \cdots < T_j^{L_j - 1}$ are the breakpoints of $\epsilon_j(t)$.

Here is an efficient algorithm for determining the optimal allocations $c^*_1, \ldots, c^*_J$ defined in Theorem 1. First sort $T_j^l, l = 1, \ldots, L_j, j = 1, \ldots, J$, in increasing order. Number them as $T_1, T_2, \ldots, T_L$. These points are the break points of $\epsilon(t)$. Let $k$ be the maximum $l$ such that $\epsilon^-(T_k) \leq C$. Note that to calculate $\epsilon^-(T_k)$ it suffices to calculate $\epsilon_j^-(T_k)$ for $j = 1, \ldots, J$; and to calculate $\epsilon_j^-(T_k)$, we can determine the $l_j$ such that $T_j^{l_j} \leq T_k < T_j^{l_j + 1}$ and then set $\epsilon_j^-(T_k) = \rho_j^{l_j + 1} t_j^l$ if $T_j^l < T_k$ and set $\epsilon_j^-(T_k) = \rho_j^l$ if $T_j^l = T_k$.

The $t_{\text{max}}$ in Theorem 1 is $T_k$. Once having determined $k$, find $k_j$ such that $T_j^{k_j} \leq T_k < T_j^{k_j + 1}$ and set $c^*_j = \rho_j^{k_j + 1}$ if $T_j^{k_j} < T_k$ or set $c^*_j = \rho_j^l + \alpha(\rho_j^{k_j + 1} - \rho_j^l)$ if $T_j^{k_j} = T_k$, where $\alpha$ is defined in Theorem 1 and can also be determined directly from the $\rho_j$’s.

3.2. The buffer-bandwidth tradeoff curve

For a given link rate $C$ let $B_{\text{min}}(C)$ be the maximum buffer contents defined by Eq. (1). The function $B_{\text{min}}(C)$ is usually referred to as the buffer-bandwidth tradeoff curve [16] (it is also known as burstiness curve [17]). For a probabilistic analysis in the Section 4, it will be useful to understand the behavior of the buffer-bandwidth tradeoff curve. To this end, for each fixed $C$ let $t(C)$ be a value of $t_{\text{max}}$ that satisfies Eq. (3). It is easily seen that $t(C)$ is non-increasing in $C$.

Theorem 2. $B_{\text{min}}(C)$ is non-increasing and convex in $C$.

Proof. We first show that $B_{\text{min}}(C)$ is non-increasing. Let $h > 0$. From Eq. (2) we have

$$B_{\text{min}}(C) - B_{\text{min}}(C + h) = \epsilon(t(C)) - \epsilon(t(C + h)) + (C + h)(C + h) - t(C)C.$$

From the concavity of $\epsilon(t)$ we have

$$\epsilon^-(t(C)) = \frac{\epsilon(t(C)) - \epsilon(t(C + h))}{t(C) - t(C + h)}.$$
From Eq. (3) we have
\[ c \leq e^{-\epsilon(t(C))}. \] (11)

Combining Eqs. (9)–(11) gives
\[
B_{\min}(C) - B_{\min}(C + h) \geq e^{-\epsilon(t(C))}[t(C) - t(C + h)] \\
+ t(C + h)(C + h) - t(C)C \geq C[t(C) - t(C + h)] \\
+ t(C + h)(C + h) - t(C)C = t(C + h)h \geq 0,
\]
which proves the first statement.

For the convexity of $B_{\min}(C)$, let $C_1 \leq C_2$ and let $h > 0$. We must show
\[
B_{\min}(C_2 + h) - B_{\min}(C_2) \geq B_{\min}(C_1 + h) - B_{\min}(C_1). \tag{12}
\]

By Eq. (2) it is equivalent to show
\[
e(\epsilon(t(C_2 + h)) - \epsilon(t(C_2))) + \epsilon(t(C_1)) - \epsilon(t(C_1 + h)) \\
\geq \epsilon((C_2 + h)(C_2 + h) - t(C_2))C_2 - t(C_1 + h))(C_1 + h) \\
+ \epsilon(t(C_1)). \tag{13}
\]

Using the arguments in the proof of monotonicity, we have
\[
e(t(C_2)) - \epsilon(t(C_2 + h)) \leq C_2 + h \tag{14}
\]
and
\[
\epsilon(t(C_1)) - \epsilon(t(C_1 + h)) \geq C_1. \tag{15}
\]

Combining Eqs. (13)–(15), we obtain Eq. (12).

From Theorem 2 we know that $B_{\min}(C)$ is a decreasing convex function of $C$. If each of the regulator functions $\epsilon_i(t)$ is piecewise linear, then it is easily shown that $B_{\min}(C)$ is a decreasing convex piecewise-linear function. Using the arguments in the proof of Theorem 2, it is straightforward to show that the optimal allocation $c_j'$ for the $j$th segregated system is increasing in $C$ and that the buffer requirement for the $j$th segregated system, $B_{\min}(j, c_j')$, is decreasing in $C$.

3.3. Delay metric

In Section 3.1, we showed how to allocate bandwidth so that — for lossless operation — the collective buffer requirement of the segregated system is equal to the buffer requirement of the multiplexed system. In other words, for the buffer metric we can find a bandwidth allocation such that the segregated system performs as well as the multiplexed system. In this section, we briefly consider a natural delay metric. We show that it is not generally true that the segregated system performs as well as the multiplexed system for the delay metric.

For the multiplexed system, the maximum delay is $d := B_{\min}/C$. For the $j$th segregated system with bandwidth $c_j$ the maximum delay is $d(j,c_j) := B_{\min}(j,c_j)/c_j$. For a given allocation, we define the maximum delay of the collective segregated system to be the maximum of the maximum delays of the individual segregated systems, that is
\[
d_{\text{seg}} := \max_{1 \leq j \leq J} d(j, c_j).
\]

The following theorem draws comparisons between the maximum delay of the multiplexed system, $d$, and the maximum delay of the collective segregated system, $d_{\text{seg}}$.

Theorem 3.

1. For all allocations $d \leq \max_{1 \leq j \leq J} d(j, c_j)$.
2. There exist concave $\epsilon_i(t)$’s such that $d < \max_{1 \leq j \leq J} d(j, c_j)$ for all allocations.
3. If $\epsilon_i(t) = \cdots = \epsilon_j(t)$ (homogeneous regulator functions), then $d = \max_{1 \leq j \leq J} d(j, c_j)$.

Proof. From Theorem 1 we have
\[
B_{\min} = \sum_{j=1}^{J} B_{\min}(j, c_j).
\]

Dividing both sides of the above by $C = c_1 + \cdots + c_J$ and using the inequality
\[
\frac{x_1 + \cdots + x_J}{y_1 + \cdots + y_J} \leq \max_{1 \leq j \leq J} \frac{x_j}{y_j},
\]
we obtain
\[
d \leq \frac{\sum_{j=1}^{J} B_{\min}(j, c_j)}{\sum_{j=1}^{J} c_j} \leq \max_{1 \leq j \leq J} \left\{ \frac{B_{\min}(j, c_j)}{c_j} \right\} = \max_{1 \leq j \leq J} d(j, c_j),
\]
which establishes the first claim.

For the second claim, we offer the following example: $C = 1$, $J = 2$, $\epsilon_i(t) = 10$ for all $t \geq 0$ and
\[
\epsilon_j(t) = \begin{cases} 
2t & \text{if } 0 \leq t \leq 5, \\
10 & \text{if } t \geq 5.
\end{cases}
\]

From Eq. (1) we have $d = 15$, $d(1, c_1) = 10/c_1$, and $d(2, c_2) = 10/c_2 - 5$. It is easily seen that for all allocations $\max(10/c_1, 10/c_2 - 5) > 15$.

The third statement follows directly from Eq. (1) and the definitions of $d$ and $d(j, c_j)$. ■

For the remainder of the paper, we will use the original buffer metric.
4. Statistical multiplexing with small loss probabilities

For VBR sources the admission region can typically be made significantly larger by allowing loss to occur with minute probabilities, e.g. loss probabilities on the order of $10^{-7}$. In this section, we use our results of Section 3 to derive the worst-case loss probabilities for the multiplexer with regulated traffic.

We consider the same system as defined in Section 2: the multiplexer consists of a link of rate $C$ which is preceded by a finite buffer. There are $J$ sources and the $j$th source has an associated regulator function, denoted by $e_j(t), t \geq 0$. In this section, we suppose that the system resources are not sufficient to provide guaranteed lossless service. In other words, we assume $B < B_{\min}(C)$, so that there exists arrival processes which meet the regulator constraints but cause the buffer to overflow. Let $P_{\text{loss}}(t)$ denote the expected fraction of time during which the buffer overflows. Our goal is to determine a bound for $P_{\text{loss}}(t)$ that holds for all combinations of arrival processes which meet the regulator constraints. To this end, we follow the methodology in Ref. [16] (which in turn is inspired by the paper [9]).

Let $a_j(t)$ be the rate at which source $j$ transmits traffic at time $t$. We view $\{a_j(t), t \geq 0\}$ as a stochastic process. Our goal is to find independent rate processes $\{a_j(t), t \geq 0\}$, $j = 1, ..., J$, which maximize the loss probability over the class of all rate processes that meet the regulator constraints. To simplify the analysis, however, we only consider rate processes of the form

$$a_j(t) = b_j(t + \theta_j),$$

where $b_j(t)$ is a deterministic periodic function with some period $T_j$, and $\theta_j$ is a random variable, uniformly distributed over $[0, T_j]$. We assume that the phases $\theta_1, ..., \theta_J$ are independent, which implies that the rate processes $\{a_j(t), t \geq 0\}$, $j = 1, ..., J$, are also independent. We refer to $b_j(t)$ as a source-$j$ rate function.

We say that a source-$j$ rate function $b_j(t)$ is feasible if

$$\int_0^{t + \tau} b_j(s) \, ds \leq \epsilon_j(t) \quad \text{for all } \tau \geq 0, \ t \geq 0. \quad (16)$$

Note that for a given rate function $b_j(t)$ and phase $\theta_j$ the amount of source-$j$ traffic sent to the multiplexer over the interval $[0, t]$ is

$$A_j(t) = \int_0^t b_j(s + \theta_j) \, ds.$$

Thus the regulator constraint

$$A_j(t + \tau) - A_j(\tau) \leq \epsilon_j(t) \quad \text{for all } \tau \geq 0, \ t \geq 0$$

is satisfied if and only if $b_j(t)$ is a feasible rate function.

As in Ref. [16], our derivation of a bound for $P_{\text{loss}}$ involves the following three steps: (i) choose a point on the buffer-bandwidth tradeoff curve and transform the original system into two independent resource systems; (ii) use adversarial rate functions for the two independent resources to obtain a bound on the loss probability for the transformed system; (iii) minimize the bound by searching over all points on the buffer-bandwidth tradeoff curve. Lo Presti et al. use an on–off rate function for their worst case rate function. Our approach differs from that of Lo Presti et al. [16] in two respects. First, we allow for generalized regulators as opposed to simple regulators. Second, we derive the true adversarial rate functions, and employ these true adversarial rate functions in the bound for $P_{\text{loss}}$ for both simple and generalized regulators.

4.1. The virtual segregated system

Fix a point $(C_v, B_v)$ on the buffer-bandwidth tradeoff curve, and consider a lossless multiplexer with total amount of bandwidth $C_v$ and buffer space $B_v$. Because the system resource pair $(B, C)$ lies below the buffer-bandwidth tradeoff curve, we must have either $C_v > C$ or $B_v > B$ or both. For this lossless system, we use Theorem 1 to allocate bandwidths $c_1^v, ..., c_J^v$ from $C_v$ and buffers $b_1^v, ..., b_J^v$ from $B_v$ such that each of the corresponding $J$ segregated systems is lossless. This collection of $J$ segregated systems is called the virtual segregated system [16].

For each $j = 1, ..., J$, fix a feasible rate function $b_j(t)$. Each rate function generates a stochastic arrival process

$$A_j(t) = \int_0^t b_j(s + \theta_j) \, ds.$$

For this arrival process, let $U_j$ be a random variable that corresponds to the steady-state utilization of the $j$th segregated system; similarly, let $V_j$ be the random variable that corresponds to the steady-state buffer contents of the $j$th segregated system. Because the $\theta_j$’s are independent across the sources, $U_1, ..., U_J$ are independent of each other and $V_1, ..., V_J$ are independent of each other.

For these fixed rate functions it can be argued [16] that

$$P_{\text{loss}} \leq P_v \left( \sum_{j=1}^J U_j > C \right) + P_v \left( \sum_{j=1}^J V_j > B \right). \quad (17)$$

(The argument in Ref. [16] is for a simple regulator. It can be easily extended to our generalized regulators.)

$P_v \sum_{j=1}^J U_j > C$ is the probability that the sum of the bandwidth processes $U_1, ..., U_J$ exceeds the nodal bandwidth $C$. The subscript $v$ indicates that the steady-state random variables $U_1, ..., U_J$ are computed based on the allocation of bandwidth $C_v$ to the $J$ segregated systems. Similarly, $P_v \sum_{j=1}^J V_j > B$ is the probability that the sum of the buffer processes $V_1, ..., V_J$ exceeds the nodal buffer capacity $B$. Again, the subscript $v$ indicates that the steady-state random variables $V_1, ..., V_J$ are computed according to the allocation of buffer $B_v$ to the $J$ segregated systems.

The Eq. (17) is the starting point of our own analysis.
Using the Chernoff bound we get

\[ P_{\text{loss}} \leq \min_{\alpha \geq 0} \left\{ \sum_{j=1}^{N} \frac{M_{U_j}^r(\alpha)}{e^{\alpha C_j}} + \min_{\alpha \geq 0} \left\{ \sum_{j=1}^{N} \frac{M_{V_j}^r(\alpha)}{e^{\alpha B_j}} \right\} \right\}, \tag{18} \]

where \( M_{U_j}^r(\alpha) \) and \( M_{V_j}^r(\alpha) \) are the moment generating functions of \( U_j \) and \( V_j \), respectively, i.e. \( M_{U_j}^r(\alpha) = E[e^{\alpha U_j}] \) and \( M_{V_j}^r(\alpha) = E[e^{\alpha V_j}] \). Since Eq. (18) is valid for all points \((C_{\alpha}, B_{\alpha})\) on the buffer-bandwidth tradeoff curve, we have

\[ P_{\text{loss}} \leq \min_{(C_{\alpha}, B_{\alpha})} \left\{ \sum_{j=1}^{N} \frac{M_{U_j}^r(\alpha)}{e^{\alpha C_j}} + \min_{\alpha \geq 0} \left\{ \sum_{j=1}^{N} \frac{M_{V_j}^r(\alpha)}{e^{\alpha B_j}} \right\} \right\}. \tag{19} \]

We emphasize that the right-hand side of Eq. (19) depends on the fixed feasible rate functions. In order to give a bound that holds for all feasible rate functions we need to maximize the right-hand side of Eq. (19) over the set of all feasible rate functions. To this end, we introduce the notion of a source-\( j \) adversarial rate function.

Corresponding to each choice of \((v, \alpha)\), we say that a source-\( j \) rate function is adversarial if (i) it is feasible, and (ii) it has the largest value of \( M_{U_j}^r(\alpha) \) and \( M_{V_j}^r(\alpha) \) among all feasible source-\( j \) rate functions. Now suppose that we can find the source-\( j \) adversarial rate functions for each choice of \((v, \alpha)\); let \( U_j^v, V_j^v, j = 1, \ldots, J \), be the corresponding steady-state random variables. We then have the following bound on \( P_{\text{loss}} \):

\[ P_{\text{loss}} \leq \min_{(C_{\alpha}, B_{\alpha})} \left\{ \sum_{j=1}^{N} \frac{M_{U_j}^r(\alpha)}{e^{\alpha C_j}} + \min_{\alpha \geq 0} \left\{ \sum_{j=1}^{N} \frac{M_{V_j}^r(\alpha)}{e^{\alpha B_j}} \right\} \right\}. \tag{20} \]

Note that by using \( M_{U_j}^r(\alpha) \) and \( M_{V_j}^r(\alpha) \), which corresponds to the source-\( j \) adversarial rate function, we have obtained in Eq. (20) a bound on \( P_{\text{loss}} \) that is valid for all combinations of feasible arrival functions. We now proceed to characterize the adversarial rate functions.

4.2. Adversarial sources

Throughout this section fix a \( v, \alpha \) and \( j \). We now focus on determining a feasible rate function which maximizes both \( M_{U_j}^r(\alpha) \) and \( M_{V_j}^r(\alpha) \) over the set of feasible rate functions. We assume that the regulator functions have the form

\[ e_j(t) = \min \left\{ \beta_j^1 t, \alpha_j^2 + \beta_j^3 t, \ldots, \alpha_j^L + \beta_j^L t \right\}. \]

Note that \( e_j(t) \) is non-decreasing, concave, piecewise-linear and sub-additive. (The analysis that follows can easily be extended to the case of more general \( e_j(t) \) which are non-decreasing, concave and sub-additive.) Without loss of generality, we also assume that Eqs. (6)–(8) hold. Note that the manner in which the allocations \((c_1^j, \ldots, c_J^j)\) are chosen (see Theorem 1) ensures that \( \rho_j^{L_j} = c_j^r = \rho_j^1 \) for all \( j = 1, 2, \ldots, J \).

For a given feasible rate function \( b_j(t) \) with period \( T_j \), the arrival rate at time \( t \) is \( a_j(t) = b_j(t + \theta_j) \) where \( \theta_j \) is uniformly distributed over \([0, T_j]\). Corresponding to this \( a_j(t) \) arrival rate process, let \( v_j(t) \) be the buffer contents and \( u_j(t) \) be the link utilization at time \( t \). Note that \( v_j(t) \) and \( u_j(t) \) are periodic with period \( T_j \). Also the steady-state random variables corresponding to \( v_j(t) \) and \( u_j(t) \) have distributions

\[ P(V_j \leq x) = \frac{1}{T_j} \int_0^{T_j} 1(v_j(s) \leq x) \, ds \]

and

\[ P(U_j \leq x) = \frac{1}{T_j} \int_0^{T_j} 1(u_j(s) \leq x) \, ds. \]

Note that these distributions do not depend on the phase \( \theta_j \) and are completely determined by the rate function \( b_j(t) \) and the link rate \( c_j^r \).

Throughout the remainder of this section we treat the case \( c_j^r > \rho_j^1 \). In Section 4.3, we deal with the simpler case \( c_j^r = \rho_j^1 \). Let

\[ \delta_j^* = \max \left\{ t > 0 : \frac{e_j(t)}{t} \geq c_j^r \right\}. \tag{21} \]

Note that since \( \rho_j^1 < c_j^r \leq \rho_j^1 \) and since \( e_j(\cdot) \) is an increasing concave function, \( \delta_j^* \) is a uniquely defined, finite and strictly positive number. We now define an important class of rate functions. Let \( T_{\text{off}} \) be such that \( 0 < T_{\text{off}} < \delta_j^* \) and let

\[ T_j = \frac{e_j(T_{\text{off}})}{\rho_j^1}. \]

Now consider a rate function \( b_j(t) \) with period \( T_j \) defined as follows:

\[ b_j(t) = \begin{cases} \epsilon_j^*(t) & 0 \leq t \leq T_{\text{off}}, \\ 0 & T_{\text{off}} \leq t \leq T_j. \end{cases} \]

Such a rate function is pictured in Fig. 2.

This rate function is completely characterized by the parameter \( T_{\text{off}} \). Note that the average arrival rate for this rate function is simply \( \rho_j^L \). Let \( S_j \) be the collection of all
rate functions of this form. Each rate function in $S_j$ is identified through its $T_{\text{off}}$ parameter.

We will show that the set $S_j$ has the following important properties:

1. Each member of $S_j$ is a feasible source-$j$ rate function.
2. All members in $S_j$ have identical $M_{U_j}^j(\alpha)$, and the members of $S_j$ maximize $M_{U_j}^j(\alpha)$ over the set of all feasible source-$j$ rate functions.
3. The member in $S_j$ which has the largest $M_{U_j}^j(\alpha)$ has, in fact, the largest $M_{U_j}^j(\alpha)$ among all feasible source-$j$ rate functions.

Hence, we will have shown that in order to find the source-$j$ adversarial rate function corresponding to each choice $(\nu, \alpha)$ we need only consider the rate functions in the set $S_j$. Further, since the rate functions in $S_j$ are characterized by a single parameter, $T_{\text{off}}$, this essentially involves a single-parameter optimization problem. We now proceed to formally state and prove the properties listed above.

**Theorem 4.** Every member of $S_j$ is a feasible rate function.

**Proof.** Fix a $T_{\text{off}}$ and let $b_j(t)$ be the corresponding member of $S_j$. It follows immediately from the definition of $b_j(t)$ that

$$
\int_0^t b_j(s) \, ds \leq \epsilon_j \quad \text{for all } 0 \leq t \leq T_j.
$$

(22)

We can, in fact, show that

$$
\int_0^t b_j(s) \, ds \leq \epsilon_j(t) \quad \text{for all } t \geq 0.
$$

(23)

To see this consider any arbitrary $t = nT_j + s$, where $n$ is some non-negative integer and $0 \leq s \leq T_j$.

$$
\int_0^t b_j(s) \, ds = \int_0^{T_j} b_j(s) \, ds + \ldots + \int_{nT_j}^{(n+1)T_j} b_j(s) \, ds
$$

$$
\quad + \int_{nT_j}^{nT_j+s} b_j(s) \, ds \leq nT_j \rho_j^L + \epsilon_j(s)
$$

$$
\leq (\epsilon_j(nT_j+s) - \epsilon_j(s)) + \epsilon_j(s) = \epsilon_j(t).
$$

The first inequality follows from Eq. (22) and from the fact that the average rate of $b_j(t)$ over any period is $\rho_j^L$. The second inequality follows because the slope of $\epsilon_j(t)$ is never less than $\rho_j^L$.

Also, because $b_j(t)$ is non-increasing over each of its periods, we have

$$
\int_{\tau}^{t+\tau} b_j(s) \, ds \leq \int_0^{t} b_j(s) \, ds \quad \text{for all } \tau \geq 0, \ t \geq 0.
$$

(24)

Combining Eqs. (23) and (24) gives the desired result. ■

**Theorem 5.** Each member of $S_j$ maximizes $M_{U_j}^j(\alpha)$ over the set of all feasible rate functions.

**Proof.** Each rate function in $S_j$ leads to the following form for $u_j(t)$, the utilization of the $j$th segregated system: $u_j(t)$ is periodic with period $T_j$ and

$$
u_j(t) = \begin{cases} c_j^r & 0 \leq t \leq D_{\text{on}} \\ 0 & D_{\text{on}} \leq t \leq T_j, \end{cases}
$$

where $D_{\text{on}} = \epsilon_j(T_{\text{off}})/c_j = (\rho_j^L/c_j^r)T_j$.

The corresponding steady-state random variable is

$$
U_j = \begin{cases} c_j^r \quad \text{with probability } \frac{\rho_j^L}{c_j^r}, \\ 0 \quad \text{with probability } \left(1 - \frac{\rho_j^L}{c_j^r}\right). \end{cases}
$$

(25)

Note that $E[U_j] = \rho_j^L$.

For any feasible source, the steady state rate at which traffic leaves the $j$th segregated system, $U_j$ (say), must have a peak value less than or equal to $c_j^r$. Further, because the segregated system is lossless, the long-run average rate at which traffic departs the $j$th segregated system must equal the long-run average rate at which traffic enters the system, which is at most $\rho_j^L$. Hence, we must have $E[U_j] \leq \rho_j^L$. Among all random variables which have a peak value less than or equal to $c_j^r$ and a mean value less than or equal to $\rho_j^L$, $U_j$ as defined in Eq. (25) has the highest moment generating function, $M_{U_j}^j(\alpha)$. This is shown in the following argument (adapted from Ref. [18]). Let $U_j^*$ be any non-negative random variable with distribution $F_{U_j^*}(x)$ with a peak value $c^* \leq c_j^r$ and mean value $\mu^* \leq \rho_j^L$. Then, since $\alpha \geq 0$,

$$
M_{U_j}^j(\alpha) - M_{U_j^*}(\alpha) = \left(\frac{\rho_j^L}{c_j^r}ight) \left( e^{\alpha c_j^r} - \frac{\rho_j^L}{c_j^r} \right) e^{\alpha x} + 1 - \int_0^{c^*} e^{\alpha x} \, dF_{U_j^*}(x)
$$

$$
\geq \left( \frac{\mu^*}{c_j^r} \right) e^{\alpha c_j^r} - \frac{\mu^*}{c_j^r} \int_0^{c^*} (e^{\alpha x} - 1) \, dF_{U_j^*}(x)
$$

$$
= \frac{1}{c_j^r} \int_0^{c^*} \left(x(e^{\alpha c_j^r} - 1) - c_j^r(e^{\alpha x} - 1)\right) \, dF_{U_j^*}(x) \geq 0.
$$

Let $b_j^*(t)$ be a rate function in $S_j$ that has the largest $M_{U_j}^j(\alpha)$.

**Theorem 6.** $b_j^*(t)$ maximizes $M_{U_j}^j(\alpha)$ among all feasible rate functions.

**Proof.** Consider any feasible source-$j$ rate function $b_j(t)$
with period $T_j$. The actual arrival rate at time $t$ is $a_j(t) = b_j(t + \theta_j)$ where $\theta_j$ is the random phase. Here, we are concerned only with the steady-state distribution of the buffer contents and the utilization rate of the $j$th segregated system which are independent of the phase. Hence, in the rest of the proof, we will, without loss of generality, set the phase to zero and consider $b_j(t)$ to be the arrival rate at time $t$. The corresponding buffer contents process, $v_j(t)$, is also periodic with period $T_j$.

In general, both $b_j(t)$ and $v_j(t)$ can have rather complicated forms with several intervals within a period where each is non-zero. However, we will first show the desired result for feasible rate functions that give a buffer content process of the form $v_j(t) > 0$ for $0 < t < \tau_j$ and $v_j(t) = 0$ for $\tau_j \leq t \leq T_j$, for some $0 < \tau_j < T_j$. For rate processes of this form we have

$$v_j(t) = \begin{cases} \int_0^t b_j(s) \, ds - c_j^* t & 0 \leq t \leq \tau_j, \\ 0 & \tau_j \leq t \leq T_j. \end{cases}$$

Note that, since $v_j(t) > 0$ for all $0 < t < \tau_j$, we must have $\tau_j \leq \delta_j$. \hfill (26)

We show next that $M_j^u(\alpha)$ corresponding to such a feasible rate function is smaller than that corresponding to $b_j(t)$. We do this by showing that there is a rate function in the set $S_j$, $\bar{b}_j(t)$, with steady-state buffer contents $\bar{v}_j$ which is stochastically larger than $V_j$ and which, hence, has a larger MGF (moment generating function).

Let $T_{\text{off}}$ be such that $\varepsilon_j(T_{\text{off}}) = c_j \tau_j$. From Eqs. (21) and (26) we get, $\varepsilon_j(T_{\text{off}}) < \varepsilon_j(\tau_j)$ if $\tau_j < \delta_j$ and $\varepsilon_j(T_{\text{off}}) = \varepsilon_j(\delta_j)$ if $\tau_j = \delta_j$. Hence, since $\varepsilon_j(\cdot)$ is non-decreasing and $\delta_j$ is uniquely defined, $T_{\text{off}} \leq \tau_j \leq \delta_j$. By definition, the rate function in $S_j$ corresponding to this $T_{\text{off}}$ is periodic with period $\tilde{T}_j = \varepsilon_j(T_{\text{off}}) / \delta_j$ and has the form

$$\bar{b}_j(t) = \begin{cases} \varepsilon_j(t) & 0 \leq t \leq T_{\text{off}}, \\ 0 & T_{\text{off}} \leq t \leq \tilde{T}_j. \end{cases}$$

The corresponding buffer contents at time $t$, $\bar{v}_j(t)$, is given as

$$\bar{v}_j(t) = \begin{cases} \varepsilon_j(T_{\text{off}}) - c_j^* t & 0 \leq t \leq T_{\text{off}}, \\ \varepsilon_j(T_{\text{off}}) - c_j^* \tau_j & T_{\text{off}} \leq t \leq \tau_j, \\ 0 & \tau_j \leq t \leq \tilde{T}_j. \end{cases}$$

Denote the corresponding steady-state random variable as $\bar{V}_j$.

Clearly, $v_j(t) \leq \bar{v}_j(t)$ for all $0 \leq t \leq T_{\text{off}}$. Note also, that we cannot have $v_j(t) > \bar{v}_j(t)$ for any $T_{\text{off}} \leq t \leq \tau_j$ since that would require $v_j(t)$ to decrease at a rate strictly faster than $c_j^*$, in order for both $v_j(t)$ and $\bar{v}_j(t)$ to be zero at $\tau_j$. Hence, we get

$$v_j(t) \leq \bar{v}_j(t) \quad \text{for all } 0 \leq t \leq \tau_j. \quad (27)$$

Also, we can show that

$$T_j \geq \tilde{T}_j. \quad (28)$$

To see this, note that the utilization rate of the $j$th segregated system with arrival rate $b_j(t)$ is $c_j^*$ whenever $v_j(t)$ is non-zero. Hence, $P(U_j = c_j^*) \geq \tau_j / T_j$. Also, since the average utilization rate must be equal to the average arrival rate, which in turn is smaller than $\rho_j^L$,

$$\rho_j^L \geq E[U_j] \geq c_j^* P(U_j = c_j^*) \geq c_j^* \frac{\tau_j}{T_j}$$

and so,

$$T_j \geq \frac{c_j^* \tau_j}{\rho_j^L} = \frac{\varepsilon_j(T_{\text{off}})}{\rho_j^L} = T_{\text{off}}.$$

Eqs. (28) and (27) imply that

$$P(V_j > x) \leq P(\bar{V}_j > x) \quad \text{for all } x \geq 0.$$

We have thus shown that $V_j$ is stochastically smaller than $\bar{V}_j$ and hence has a smaller MGF. It is immediate from the definition of $b_j^*(t)$ that $M_j^u(\alpha)$ is smaller than the MGF of $b_j^*(t)$.

We now extend this argument to the case of a general feasible rate function $b_j(t)$. Assume, without loss of generality, that the corresponding buffer content process $v_j(t)$ has $m$ (some positive integer) non-zero portions within a single period, identified by $v_j^1, v_j^2, \ldots, v_j^m$ in the following manner:

$$v_j(t) = \begin{cases} 0 & 0 \leq t \leq t_j^1, \\ v_j^1(t - t_j^1) & t_j^1 \leq t \leq t_j^1 + t_j^2, \\ v_j^2(t - t_j^2) & t_j^2 \leq t \leq t_j^2 + t_j^2, \\ \vdots & \\ v_j^m(t - t_j^m) & t_j^m \leq t \leq t_j^m + t_j^m, \\ 0 & t_j^m + t_j^m \leq t \leq T_j, \end{cases}$$

where $t_j^i > 0, i = 1, 2, \ldots, m$, and $t_j^i \geq t_j^{i-1} + t_j^{i-1}, i = 2, \ldots, m$. Here, $t_j^1$ and $t_j^i + t_j^{i-1}$ represent the end points of the $i$th non-zero portion.

We can express each non-zero portion $v_j^i(t)$ as a periodic function, with period $T_j$, of the following form:

$$v_j^i(t) = \begin{cases} \int_{t_j^i}^{t_j^i + t_j^i} b_j(s) \, ds - c_j^* t & 0 \leq t \leq t_j^i, \\ 0 & t_j^i \leq t \leq T_j. \end{cases}$$

Let $V_j^i$ denote the corresponding steady-state random
variable with MGF $M_{V_j}^v(\alpha)$. It is easily seen that

$$V_j = \left\{ \begin{array}{ll} V_j^1 & \text{with probability } \left( \frac{\tau_j^1}{\sum_{i=1}^m \tau_j^i} \right) T_j, \\ \vdots & \\ V_j^m & \text{with probability } \left( \frac{\tau_j^m}{\sum_{i=1}^m \tau_j^i} \right) T_j, \end{array} \right.$$

and hence,

$$M_{V_j}^v(\alpha) = \sum_{i=1}^m \left( \frac{\tau_j^i}{\sum_{i=1}^m \tau_j^i} \right) M_{V_j}^i(\alpha). \quad (29)$$

Now, the $i$th non-zero portion, when viewed in isolation, has the simple form assumed in the earlier part of the proof, and can be viewed as the buffer contents at time $t$ of the $i$th segregated system subject to the following arrival rate:

$$b_j(t) = \left\{ \begin{array}{ll} b_j(t_j + t) & 0 \leq t \leq t_j, \\ 0 & t_j \leq t \leq T_j. \end{array} \right.$$

Note that $b_j(t)$ is also a feasible source-j rate function with period $T_j$. Hence, from our earlier argument, we know that $M_{V_j}^v(\alpha)$ is smaller than the MGF that corresponds to $b_j(t)$. Hence, from Eq. (29), we get that $M_{V_j}^v(\alpha)$ is also smaller than that corresponding to $b_j(t)$. We have thus shown that $b_j(t)$ maximizes $M_{V_j}^v(\alpha)$ over the set of all feasible source-j rate functions.

From Theorems 5 and 6 the following corollary is immediate.

**Corollary 1.** There exists a rate function belonging to $S_j$ which maximizes both $M_{V_j}^v(\alpha)$ and $M_{V_j}^v(\alpha)$ over the set of all feasible source-j rate functions. This rate function is the required source-j adversarial rate function corresponding to $(\nu, \alpha)$.

Thus, when $c_j^* > \rho_j^L$, in order to find the source-j adversarial rate function corresponding to any choice of $(\nu, \alpha)$ we need only consider the rate functions in set $S_j$.

4.3. The case of $c_j^* = \rho_j^L$

We now deal with the special case of $c_j^* = \rho_j^L$. Then $c_j^* = \rho_j^L$, it is easily seen that the adversarial source-j rate function has the following form:

$$b_j(t) = \epsilon_j^*(t) \quad \text{for all } t \geq 0.$$

Clearly, this rate function satisfies Eq. (16). We will drop the requirement of periodicity for this special case and consider this rate function to be feasible. (Alternatively, we could consider this rate function to be trivially periodic with a period of $+\infty$.) This rate function leads to the following degenerate form of the corresponding steady-state random variables:

$$U_j^* = c_j^* \quad \text{with probability } 1$$

$$V_j^* = b_j^* \quad \text{with probability } 1$$

with corresponding MGFs

$$M_{U_j}^v(\alpha) = e^{\alpha c_j}, \quad M_{V_j}^v(\alpha) = e^{\alpha b_j}$$

which are clearly the largest possible values for these quantities.

In Section 5, we consider input sources that are constrained by simple regulators and describe a heuristic procedure to efficiently compute $P_{\text{loss}}$ for this case.

5. Simple regulators

In the last section, we showed that for each segregated system there exists a rate function in $S_j$ which is adversarial to the greatest extent permitted by the regulator constraint $\epsilon_j(t)$. The set $S_j$ includes the extremal periodic on-off rate functions studied in Ref. [16]. It is therefore natural to pose the following question: Is the extremal periodic on-off rate function adversarial?

In this section, we focus our attention on simple regulators $\epsilon_j(t) = \min\{\rho_j^L t, \sigma_j^2 + \rho_j^L t\}$. We first show that the adversarial rate function in $S_j$ is not the extremal on-off rate function used in LoPresti et al. This implies that the use of on-off rate functions, as in LoPresti et al., can lead to overly optimistic admission regions. We then present an algorithm for calculating $P_{\text{loss}}$ using the adversarial rate functions for each of the sources. This involves, for each source $j$, a search to find the $T_{\text{off}}$ that leads to the most adversarial behavior.

We also note at this juncture that the sub-adversariality of the on-off rate functions was first observed by Doshi [6,7]. He provides a counter-example that shows that a feasible rate function that is not on-off can lead to larger losses than a feasible on-off rate function. We provide an explicit and computationally efficient characterization of the most adversarial rate function.

5.1. Sub-adversariality of on-off rate functions

Fix a segregated system $j$. For ease of notation, let $P_j = \rho_j^L$, $\rho_j = \sigma_j^2$ and $\sigma_j = \sigma_j^2$; the traffic constraint function is thus given by $E_j(t) = \min\{P_j t, \sigma_j + \rho_j t\}$. We study three different rate functions, all complying with the imposed traffic constraint function. All these rate functions belong to $S_j$. Fig. 3a gives the plots of the traffic constraint function, $E_j(t)$, and the actual arrivals, $A_j(t)$, of the studied rate functions. Fig. 3b depicts the arrival rate function $b_j(t)$. Fig. 3c gives the link utilization $u_j(t)$. Fig. 3d shows the buffer contents of the segregated system. Note that traffic leaves
the segregated system at rate $c_j$ whenever the buffer is non-empty. For the remainder of this section, we remove the subscript $j$ from all notations.

Rate function 1 is the extremal on–off rate function used by Elwalid et al. [9] and LoPresti et al. [16]. It transmits at peak rate $P$ for $T_{on_1} = \sigma(P - \rho)$, at which time the token pool is completely emptied. The rate function then turns off and waits for $T_{off_1} = \sigma/\rho$, allowing the token pool to be refilled with $\sigma$ tokens. The rate function then transmits the next burst of size $PT_{on_1}$ at peak rate. The buffer is filled at rate $P - c$ while the source transmits at rate $P$. The maximum buffer contents is therefore $b = (P - c)T_{on_1}$. After the source has turned off, the buffer is drained at rate $c$. The utilization of the segregated system is $c$ for $D_{on_i} = T_{on_i} + b/c$ and 0 for $D_{off_i} = T_{off_i} - b/c$. Rate Function 1 and the other two rate functions are summarized in Table 1.

<table>
<thead>
<tr>
<th>Rate function</th>
<th>$T_{on}$</th>
<th>$T_{off}$</th>
<th>$T$</th>
<th>$D_{on}$</th>
<th>$D_{off}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\sigma$</td>
<td>$\sigma$</td>
<td>$\sigma P$</td>
<td>$\sigma P$</td>
<td>$\frac{1 - \rho + P(1 - 1/c)}{\rho(P - \rho)}$</td>
</tr>
<tr>
<td>2</td>
<td>$\sigma$</td>
<td>$\sigma$</td>
<td>$\sigma c$</td>
<td>$\sigma$</td>
<td>$\frac{c - \rho}{\rho}$</td>
</tr>
<tr>
<td>3</td>
<td>$u$</td>
<td>$u + \sigma$</td>
<td>$\frac{\sigma + up}{c}$</td>
<td>$\frac{(up + \sigma)(c - \rho)}{\rho c}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 1
On and off times of rate functions and corresponding segregated systems

Fig. 3. Illustration of rate functions 1, 2 and 3. (a) Amount of traffic arriving to the segregated system $A_j(t)$. (b) Arrival rate process $b_j(t)$. (c) Utilization process $u_j(t)$. (d) Buffer content process $v_j(t)$.
Rate function 2 transmits at peak rate \( P \) for \( T_{\text{on}} \), it then continues sending traffic at rate \( \rho \) into the segregated system until the corresponding buffer process hits zero. As is the case for rate function 1, the buffer is filled up to \( b \) at rate \( P - c \); it is now however drained at rate \( c - \rho \). The source transmits therefore greedily for \( T_{\text{on}} = T_{\text{on}_1} + b(c - \rho) \). It then shuts off, waits until the token pool is replenished, and repeats the described transmission pattern.

Rate function 3 generalizes the rate function behaviors discussed so far. It transmits greedily for \( u, T_{\text{on}_1} \leq u \leq T_{\text{on}_2} \), that is, it transmits at rate \( P \) for \( T_{\text{on}} \), and then at rate \( \rho \) for \( u - T_{\text{on}} \). The corresponding buffer process is shown in Fig. 4d. The buffer is filled to \( b \) at rate \( P - c \). It is then drained at rate \( c - \rho \) during the interval \( [T_{\text{on}}, u] \). Let \( v(u) \) denote the buffer contents at time \( u \); clearly, \( v(u) = \sigma + u(\rho - c) \). The remaining traffic \( v(u) \) is drained at rate \( c \). Loosely speaking, rate function 3 lies between the extremes of rate function 1 and rate function 2: it is equivalent to rate function 1 for \( u = T_{\text{on}} \), and is equivalent to rate function 2 for \( u = T_{\text{on}_2} \).

We now turn our attention to the buffer processes of the described rate functions. Let \( V_1, V_2, \) and \( V_3 \) be random variables denoting the buffer contents corresponding to rate function 1, 2, and 3. It can be easily verified that \( V_1 \) and \( V_2 \) have identical distribution functions:

\[
P(V_1 \leq x) = P(V_2 \leq x) = 1 - \omega + x\frac{\omega}{b}, \quad 0 \leq x \leq b,
\]

where \( \omega = \rho/c \) is the long run probability that the segregated system is busy. The distribution function of \( V_3 \) is given by

\[
P(V_3 \leq x) = \begin{cases} 
1 - \omega + \frac{\omega}{b} \frac{P\sigma}{(P - \rho)(\rho + \sigma)} & \text{for } 0 \leq x \leq v(u), \\
1 - \omega + \frac{\omega}{b} \frac{c\sigma}{(c - \rho)(\rho + \sigma)} + \frac{u\rho^2}{(c - \rho)(\rho + \sigma)} - \frac{\rho^2}{(c - \rho)c} & \text{for } v(u) \leq x \leq b.
\end{cases}
\]

Next, we show that \( V_3 \) is strictly stochastically larger than \( V_1 \) and \( V_2 \) whenever \( T_{\text{on}_1} < u < T_{\text{on}_2} \). First, note that

\[
\frac{P\sigma}{(P - \rho)(\rho + \sigma)} < 1 \quad \text{for } u > T_{\text{on}_1}.
\]

Furthermore, it can be shown that

\[
\frac{x\omega}{b} \frac{c\sigma}{(c - \rho)(\rho + \sigma)} + \frac{u\rho^2}{(c - \rho)(\rho + \sigma)} - \frac{\rho^2}{(c - \rho)c} < \frac{\omega}{b}
\]

for \( u < T_{\text{on}_2} \), and \( x < b \). Hence,

\[
P(V_3 \leq x) < P(V_1 \leq x) \quad \text{for } 0 \leq x \leq b.
\]  \hspace{\text{20pt}} (31)

Thus \( V_3 \) is strictly stochastically larger than \( V_1 \) and \( V_2 \). This implies that the moment generating function of \( V_3 \) is larger than that of \( V_1 \) and \( V_2 \). The loss probability computed with rate function 3 is therefore larger than that corresponding to rate functions 1 and 2. Rate function 1, which is used in
Table 2
The moment generating function of the buffer process \( V_t \) and its derivatives

| \( M_{V_t}(\alpha) \) | \( 1 - \omega + \frac{\omega \sigma}{ab(\mu + \alpha)^2} \left( \frac{\rho(c - \rho)}{P - \rho(c - \rho)} e^{\alpha \omega(t)} + \frac{1}{1 - \omega} e^{\alpha \omega} \right) - \frac{P}{P - \rho} \) |
| \( \frac{\partial M_{V_t}(\alpha)}{\partial \alpha} \) | \( \frac{\omega \sigma}{ab(\mu + \alpha)^2} \left( \frac{\rho(c - \rho)}{P - \rho(c - \rho)} \left[ \alpha \omega (c - \rho) - 1 \right] e^{\alpha \omega(t)} + \frac{1}{1 - \omega} (\alpha \omega - 1) e^{\alpha \omega} + \frac{P}{P - \rho} \right) \) |
| \( \frac{\partial^2 M_{V_t}(\alpha)}{\partial \alpha^2} \) | \( \frac{\omega \sigma}{ab(\mu + \alpha)^2} \left( \frac{\rho(c - \rho)}{P - \rho(c - \rho)} \left[ \alpha \omega^2 (c - \rho)^2 - 2 \alpha \omega (c - \rho) + 2 \right] e^{\alpha \omega(t)} + \frac{1}{1 - \omega} \alpha^2 \omega (c - \rho)^2 - 2 \alpha \omega (c - \rho) + 2 \right) e^{\alpha \omega} + \frac{2P}{P - \rho} \) |

LoPresti et al., can therefore lead to overly optimistic admission decisions.

5.2. Finding the most adversarial rate function

In this section, we espouse the problem of finding the most adversarial rate function among the rate functions fitting the template of rate function \( T_3 \). Toward this end we need to find the on-time \( u \) that maximizes the moment generating function of \( V_t \). The moment generating function of \( V_t \) defined as \( M_{V_t}(\alpha) = E[e^{\alpha V_t}] \), and its derivative with respect to \( u \) are given in Table 2. The table gives furthermore the first and second derivative of \( M_{V_t}(\alpha) \) with respect to \( \alpha \). These expressions are needed for the computation of \( P_{\text{loss}} \) (see Section 5.3).

Setting \( \frac{\partial M_{V_t}(\alpha)}{\partial \alpha} \) to zero, we obtain

\[
\left( \alpha \mu u + \alpha \sigma + \frac{\omega}{1 - \omega} \right) e^{-\alpha \omega(c - \rho) u} = \frac{(P - \rho) e^{\alpha \omega} - P(1 - \omega)}{(1 - \omega)(P - \rho) e^{\alpha \omega}}. \tag{32}
\]

It can be shown that Eq. (32) has exactly one solution in \([T_{on}, T_{on} + T_{on}]\). It can be computed efficiently with Newtons method [22] using \( (T_{on} + T_{on})/2 \) as initial solution. We observed in our numerical investigations that \( (T_{on} + T_{on})/2 \) provides in many cases a good approximation of the solution of Eq. (32). Rate function 3 with \( u = (T_{on} + T_{on})/2 \) may therefore be used as an approximation of the most adversarial rate function.

5.3. Numerical examples

In this section, we report on some numerical investigations with the most adversarial rate function. For the computation of \( P_{\text{loss}} \) we essentially follow the numerical procedure outlined in LoPresti et al. [16]. In addition to the computations conducted by LoPresti et al., however, we solve Eq. (32) in order to find the most adversarial rate function.

Table 3
Leaky bucket parameters of sources

<table>
<thead>
<tr>
<th>Class</th>
<th>( \rho ) (Mbps)</th>
<th>( P ) (Mbps)</th>
<th>( \sigma ) (cells)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
<td>1.5</td>
<td>225</td>
</tr>
<tr>
<td>2</td>
<td>0.15</td>
<td>6</td>
<td>24.4</td>
</tr>
</tbody>
</table>

We compare our approach with that of Elwald et al. [9] and LoPresti et al. in Fig. 4. We use the same two source classes (see Table 3) as LoPresti et al. in [16, Fig. 15]. They in turn use the same parameters as Elwald et al. in Ref. [9, Fig. 13]. The bandwidth and buffer size are \( C = 45 \text{ Mbps} \) and \( B = 1000 \text{ cells} \) (1 cell = 53 bytes) in this example. The figure depicts the admission region corresponding to the admission control criterion \( P_{\text{loss}} \leq 10^{-7} \). We observe that employing the truly adversarial rate function results in an admission region that lies generally between that of Elwald et al. and LoPresti et al. Because we are using the truly adversarial sources, our approach has a smaller admission region than LoPresti et al. Our approach admits slightly less connections than the approach of LoPresti et al. in the range \( 0 \leq k_1 \leq 75 \). For \( k_1 = 0 \), we admit 172 connections of class 2 while LoPresti et al. allow 175 connections. The gap between the two approaches widens for \( k_1 > 75 \). This is due to the fact that the optimal resource allocation according to Theorem 1 allocates \( c_1' = \rho_2 \) in this region. Rate function 3 degenerates to the form described in Section 4.3 for this allocation. The moment generating function of this rate function is significantly larger that corresponding to rate function 1, resulting in a noticeably smaller admission region for our approach. The gap is at its widest for \( k_1 = 81 \). Our approach admits 41 connections of class 2 while LoPresti et al. admit 51 connections.

In Fig. 5 we consider a single source class with \( P = 5 \text{ cells/s} \), \( \rho = 2.5 \text{ cells/s} \) and \( \sigma = 20 \text{ cells} \). (This choice of parameters is inspired by Oechslin [19,20].) We consider transmitting the traffic of 200 of these sources over a link of capacity \( C = 575 \text{ cells/s} \). The figure shows \( P_{\text{loss}} \) computed according to our approach (RRR) and LoPresti et al. as a function of the buffer size \( B \). We observe that both approaches give about the same loss probability for buffers smaller than 50 cells. For large buffers, however, the approaches differ greatly. For \( B = 1400 \text{ cells} \) the loss probability computed according to LoPresti et al. is about one order of magnitude smaller that computed with the most adversarial rate function. For \( B = 1700 \text{ cells} \) the gap widens to roughly two orders of magnitude. We conclude from the figure that the approach of LoPresti et al. can significantly underestimate the loss probability.
6. Conclusion

We have studied a buffered multiplexer that is fed by regulated traffic streams. We have considered both lossless and lossy multiplexing. For lossless multiplexing, we have shown how to allocate bandwidth and buffer to the individual traffic streams such that the resulting segregated systems are lossless. For lossy multiplexing we have re-examined the three step procedure (originally proposed by LoPresti et al. [16]) for estimating the loss probability: (i) choose a point on the buffer-bandwidth tradeoff curve and transform the original system into two independent resource (buffer and bandwidth) systems; (ii) use adversarial sources for the two independent resources to obtain a bound on the loss probability of the transformed system; (iii) minimize the bound by searching over the buffer-bandwidth tradeoff curve. One of our contributions is to generalize this three step procedure developed in Ref. [16] for the simple regulator (i.e. a peak rate limiter in series with a leaky bucket) to more general traffic regulators, that are even more general than cascaded leaky buckets. For these general traffic regulators, we provide an explicit result and efficient algorithm to transform the system in step (i). We also study the properties of the buffer-bandwidth tradeoff curve in this more general setting.

Our main contribution is an explicit characterization of the adversarial sources for the transformed problem in step (ii). We prove that the most adversarial source is not a periodic on–off source. Even for the simple regulator, the most adversarial source is not a periodic on–off source. Thus using a periodic on–off source in step (ii) of the three step procedure may underestimate the loss probability and lead to overly optimistic admission decisions. We provide an efficient algorithm to calculate the estimate of the loss probability based on the truly adversarial sources. For the simple regulator, we conduct numerical evaluations of the estimation procedure involving the truly adversarial sources. Our numerical results indicate that using on–off sources instead of the truly adversarial sources my overestimate the number of admissible streams by up to 23% in some scenarios.

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References


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