# Using the Network Load for Admission Control in OBS Networks: a Multilink Approach

Igor M. Moraes and Otto Carlos M. B. Duarte

***Abstract*—In this article, we analyze the performance of the Load-Level-Based Admission Control mechanism (LLAC) for optical burst-switched networks in a multilink scenario. The goal of our mechanism is to differentiate the blocking probability of a given service class according to the network load and a class-associated parameter, called load level. We develop a multilink analytical model based on the reduced load approximation method to analyze the proposed mechanism in more realistic scenarios. The multilink model provides an estimation error up to 13 times lower than the one provided by the single-model for the analyzed configurations. Both are compared with simulation results. In addition, our results show that the load-level-based mechanism effectively differentiates the services in all analyzed configurations, when compared with other similar mechanisms.**

***Index Terms*—Optical burst switching; quality of service; differentiated services; admission control.**

## I. Introduction

Optical Burst Switching (OBS) is an optical data transport technique proposed to ensure the efficient use of the bandwidth offered by Wavelength-Division Multiplexing (WDM) networks [1], [2]. Although optical transmissions can reach the magnitude of terabits per second, electronic switches do not achieve this capacity nowadays. Because OBS nodes entirely perform the switching task in the optical domain, these nodes do not require the optical-electronic-optical (OEO) conversion currently used by most switching techniques employed in WDM networks. Thus, the data transport rate of WDM networks is not limited by the OEO conversion.

There are two types of nodes in OBS networks: edge nodes and core nodes. Edge nodes perform the burst assembly process where packets with the same destination address are aggregated to be sent in a single burst. Before the burst transmission, the aggregating node sends a control packet to establish an all-optical path in an out-of-band signaling channel. When the control packet arrives at an OBS core node in the source-destination path, it is electronically converted and processed. If there are available resources, the core node reserves the required resources for the upcoming burst. Otherwise, the burst is blocked. Most signaling protocols proposed for OBS networks do not require error messages or reservation acknowledgments from OBS nodes.

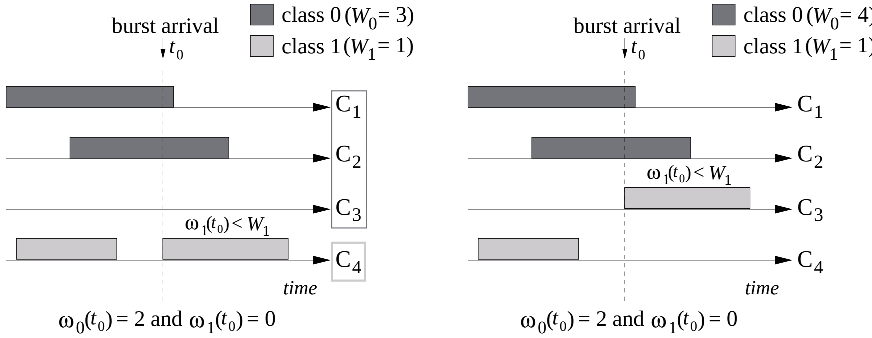
One of the main aspects that differs optical burst switching from optical circuit switching is that, in OBS, the network resources are only held for the burst switching and transmission time. In optical circuit switching, an explicit control packet must be sent to tear down the circuit. Furthermore, OBS nodes do not need buffers to store and process bursts as in optical-packet switched networks. This is an advantage because optical buffers are still experimental.

Igor M. Moraes and Otto Carlos M. B. Duarte are with Grupo de Teleinformática e Automação (GTA), Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil (e-mails:{igor,otto}@gta.ufrj.br).

Quality-of-service (QoS) support is essential in OBS networks. Despite the bandwidth availability, the best-effort service is not able to guarantee the QoS required by new applications [3]–[5]. The main problem is that only a few tens of wavelengths are available per optical link nowadays. As a burst occupies one wavelength, future bursts may be blocked depending on the load offered to the network. In addition, most of the existing QoS mechanisms proposed for electronic packet switching are based on buffer management [6]. To employ these mechanisms in OBS networks, optical buffers are needed. Optical memories, however, are not yet available and bursts can only be delayed by fiber delay lines (FDLs) [7]. Therefore, it is necessary to convert the optical signal to the electronic domain at each edge node, which limits the data transport rate. These characteristics lead to the development of specific QoS mechanisms for OBS networks.

In a previous work [8], we proposed an admission control mechanism for providing service differentiation in OBS networks. The idea behind this mechanism, called Load-Level-based Admission Control Mechanism (LLAC), is to reserve a different amount of wavelengths in a link for each service class. The number of wavelengths that a class can occupy in a link is defined by a parameter called *load level*. Thus, LLAC differentiates the blocking probability experienced by a given class, admitting bursts according to the network load and the load level associated to this class. To evaluate the performance of the load-level-based mechanism, we considered a single-link model. The single-link model provides a good approximation for the blocking probability of each service class in a link, but this model does not consider that the blocking probability in a link is influenced by other links of the network. Thus, using the single-link model to represent realistic network scenarios has some shortcomings. First, this model does not take into account the wastage of capacity on links traversed before by blocked bursts. Second, the single-link model does not consider the reduction on the load offered to core nodes because of the blocking of bursts along source-destination path. For OBS networks, these two factors must be considered in the development of more realistic models.

In this article, we derive a multilink analytical model for the load-level-based mechanism based on the reduced load fixed-point approximation for OBS networks developed by Rosberg *et al.* [9]. The main goal of this article is to analyze the performance of LLAC in a real network topology, using




(a) The static mechanism.

(b) The dynamic mechanism.

Fig. 1. An example of how the static and dynamic mechanisms work.

the developed multilink model. The load-level-based mechanism always performs well and, according to the results, the multilink model provides a more accurate blocking probability estimation than the conventional single-link model for realistic scenarios. Both models are compared with simulation results. In addition, for all analyzed configurations, LLAC provides a lower blocking probability for the high-priority class in comparison with other admission control mechanisms [10].

The remainder of the article is organized as follows. In Section II, we discuss the works related to quality of service in OBS networks. The LLAC mechanism is presented in Section III. We then derive the multilink analytical model for LLAC in Section IV. After that, in Section V, we analyze the performance of the load-level-based mechanism in comparison with other similar mechanisms, based on their multilink models. Conclusions about this work are presented in Section VI.

## II. Related Work

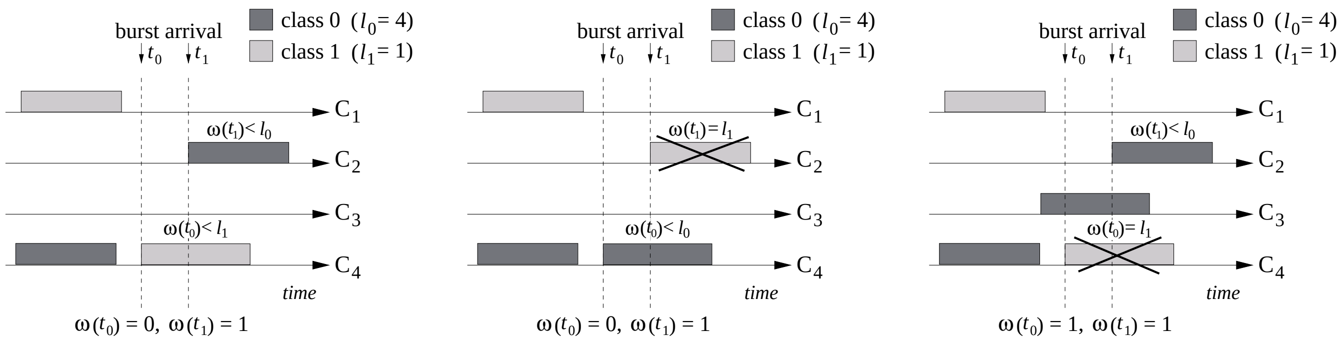
Several mechanisms have been proposed to address QoS support in optical-burst switched networks. Some approaches are based on the modification of signaling protocols [7] and also on burst preemption [11]–[13]. The modification of signaling protocols, however, may increase the end-to-end delay of high-priority bursts because of the extra offset introduced [14] and burst preemption are hard to implement in practice. Another approach is to reserve a different number of wavelengths for each service class in a link. Thus, a burst of a high-priority class has lower blocking probability than a burst of a low-priority class because it has more resources reserved. This is the idea of the admission control mechanisms [15], [16] for OBS networks. Basically, these mechanisms differ in how the wavelengths are reserved for each service class.

Zhang *et al.* [16] propose two admission control mechanisms: a static and a dynamic mechanism. Both are based on the number of wavelengths occupied by each service class. Let $W_i$ be the maximum number of wavelengths that a class $i$ can occupy and $\omega_i(t)$ be the number of occupied wavelengths in a link by class $i$ at time $t$. A burst of class $i$ will be admitted at time $t_0$ only if

$$\omega_i(t_0) < W_i. \tag{1}$$

Although both mechanisms have the same admission criterion as in Eq. (1), the wavelength reservation of each class is different for each mechanism. The static mechanism reserves a fixed set of wavelengths $W_i$, in a given link, for bursts of a given service class $i$. In other words, if the first $W_i$ wavelengths of a link are reserved for class $i$, burst of class $i$ can only occupy the wavelengths $C_j \in \{j|1 \leq j \leq W_i\}$. On the other hand, the dynamic mechanism reserves a fixed number of wavelengths $W_i$ (instead of a fixed set) for bursts of a given service class $i$. Thus, a burst belonging to class $i$ can occupy any available wavelength in a given link, as long as the admission criterion in Eq. (1) is satisfied. In addition, with the dynamic mechanism, high-priority bursts are admitted if there is at least one available wavelength. In other words, let $h$ be the high-priority class, $W_h$ is always equal to the link capacity in terms of wavelengths. Therefore, there is no guarantee that bursts belonging to a low-priority class $i$ will be able to occupy all of its $W_i$ authorized wavelengths because all wavelengths of a link might be already occupied by high-priority bursts. Fig. 1 shows an example of how these two mechanisms work for two service classes in a four-wavelength link. Class 0 is the high-priority class. With static mechanism, three wavelengths are reserved for bursts of class 0 ($W_0 = 3$ with $C_1$, $C_2$, and $C_3$ reserved). Bursts of class 1 can occupy only one wavelength ($W_1 = 1$ with $C_4$ reserved). With dynamic mechanism, bursts of class 0 can occupy any available wavelength ($W_0 = 4$) and bursts of class 1 can occupy, at most, one wavelength ($W_1 = 1$). For the scenario shown in Fig. 1, if a burst of class 1 arrives at time $t_0$, it is admitted because the condition in Eq. (1) is satisfied. With static mechanism, as shown in Fig 1(a), this burst must occupy the wavelength $C_4$. Fig 1(b) shows that, with the dynamic mechanism, a burst of class 1 can occupy the available wavelengths $C_3$ or $C_4$, because there is no specific wavelengths reserved for each class.

For the static and dynamic mechanisms, a node must keep track of the number of wavelengths occupied by bursts of each service class to guarantee that the number of wavelengths occupied by bursts of a given class $i$ does not exceed $W_i$. Consequently, every node must store a large number of states, which is not desirable [17]. In order to benefit high-priority bursts and also reduce the number of states stored by nodes, we have proposed an admission control mechanism, described in Section III, that does not require the knowledge of what service class occupies what wavelength in a given link.




(a) Bursts of both classes are admitted. (b) Bursts of class 1 are blocked in $t_1$. (c) Bursts of class 1 are blocked in $t_0$.

Fig. 2. Examples of how the load-level-based mechanism works.

## III. The Load-Level-based Admission Control Mechanism

In this section, we describe the Load-Level-based Admission Control mechanism (LLAC). We assume that the network employs a signaling protocol that does not require a positive acknowledgement for sending a burst, for example, JET (Just-Enough Time) or JIT (Just-In Time) [1]. We also assume that bursts arrive in the same order as their control packets at each node [16]. In addition, we consider that each OBS node supports full wavelength conversion and a burst requires only one wavelength during its transmission. The use of a protocol without acknowledgements implies that all network nodes must implement an admission control mechanism. In this kind of protocol, a burst is sent after the control packet without waiting for an acknowledgment. Therefore, when a burst is sent, an edge node cannot guarantee that the number of occupied wavelengths in each link of the source-destination path satisfies the admission criterion. Just after receiving and analyzing the control packet, a node can determine if the number of occupied wavelengths is in accordance with the admission criterion at the moment of the burst arrival. Thus, to guarantee the service differentiation, LLAC must be implemented also on core nodes.

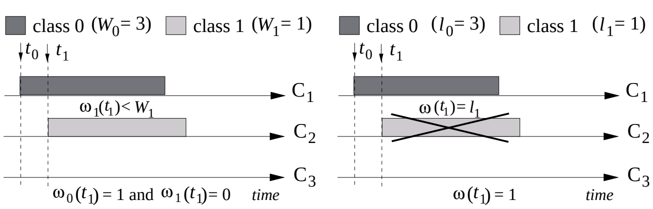
The load-level-based mechanism defines a parameter for each service class $i$ named *load level*, $l_i$. The load level must be configured at each node of the network and indicates the maximum number of wavelengths that bursts of a given class $i$ can occupy. If we define $W$ as the number of wavelengths in a given link, the inequality $0 < l_i \leq W$ always holds for every class $i$. The load level is used by LLAC to differentiate the burst blocking probability experienced by each service class. Let $\omega(t)$ be the total number of occupied wavelengths at time $t$. A burst of a class $i$ arriving at time $t_0$ is admitted if at $t_0$

$$\omega(t_0) < l_i. \quad (2)$$

Otherwise, the burst is blocked without sending any error message back to the edge node. Therefore, when the load level of class $i$ is set to a higher value, the burst blocking probability decreases. It is worth noting that the admission criterion of LLAC is based on the total number of occupied wavelengths, and not on the number of occupied wavelengths for bursts of class $i$, as occurs in the static and dynamic mechanism. This is the key point of the load-level-based mechanism. Instead of considering the number of occupied wavelengths per class, we only care about the total number of occupied wavelengths in the link. Therefore, with LLAC a node stores fewer states than with other mechanisms. The load-level-based mechanism only stores the load level of each class and the total number of occupied wavelengths. Let $n$ be the number of classes and $W$ be the capacity of a link in wavelengths, a node stores $n+1$ states with LLAC. On the other hand, a node stores $n+W$ with static or dynamic mechanisms because they must keep track of the number of wavelengths occupied by bursts of each class. Today, optical commercial switches are capable to deal with up to 128 wavelengths per fiber, each one with 10 Gb/s of capacity. On the other hand, DiffServ architecture defines four different service classes, also called Per-Hop Behaviors (PHBs). Thus, a node only stores 5 states with LLAC instead of 132 states required by the static or dynamic mechanisms. In fact, static and dynamic mechanisms can use the information available on the signaling protocols to reduce the number of states required. These protocols, however, must be changed to inform the class of a burst that occupies a given wavelength. With LLAC, we do not need to change the signaling protocols because only the number of occupied wavelengths is required.

Fig. 2 shows three examples of how LLAC works for two service classes in one link with four wavelengths ($W = 4$). The high-priority class is class 0. The load level of classes 0 and 1 are $l_0 = 4$ and $l_1 = 1$, respectively. For the situation illustrated by Fig. 2(a), when bursts belonging to class 1 and class 0 arrive, respectively, at times $t_0$ and $t_1$ they are admitted because the condition in Eq. (2) is satisfied. In Figs. 2(b) and 2(c) bursts belonging to class 1 are blocked because at its arrival time there is already one wavelength occupied and the load level of class 1 is $l_1 = 1$. In this example, bursts of class 1 are only admitted when no wavelength is occupied at its arrival time. This shows that LLAC is more aggressive against low-priority classes than the static and dynamic mechanisms. These two mechanisms admit bursts according to the number of wavelengths occupied by each service class in a link. The proposed load-level-based mechanism admits bursts based on the total number of occupied wavelengths in a link, no matter what class occupies a given wavelength.

Figs. 3(a) and 3(b) show the differences of the load-level-based and the dynamic mechanisms for a scenario of one link with three wavelengths ($W = 3$). We assume $W_0 = 3$ and $W_1 = 1$ for the dynamic mechanism and $l_0 = 3$ and $l_1 = 1$ for LLAC. In Figs. 3(a) and 3(b), a burst of class 0 arrives at instant $t_0$ and is allocated in wavelength $C_1$. After that, a burst belonging to class 1 arrives at $t_1$. In the dynamic mechanism, this burst can be allocated in wavelengths $C_2$ or $C_3$ because $W_1 = 1$ and there are no wavelengths occupied by bursts of class 1. On the other hand, LLAC blocks bursts of class 1 because $l_1 = 1$ and one wavelength is already occupied by a burst, no matter its class. In this example, LLAC does not block bursts of class 1 in only one situation: when the arrival time of a burst belonging to class 1 is equal to $t_0$. On the other hand, the dynamic mechanism blocks bursts of class 1 when one wavelength is occupied by another burst of class 1, or when all wavelengths are occupied by bursts of class 0. Moreover, in comparison with LLAC, the static mechanism is also less aggressive against class 1 traffic, because this mechanism always reserves at least one wavelength for this class. The aggressiveness against low-priority traffic is in fact the main advantage of the LLAC mechanism. The probability that a burst belonging to class 0 finds a wavelength occupied by a burst of class 1 at an instant $t$ is small because LLAC admits a lower number of bursts belonging to class 1. As a consequence, the contention for network resources occurs, most of the time, for bursts of class 0. Thus, the burst-blocking probability of class 0 is almost exclusively a function of the amount of high-priority traffic. This fact results in a better performance of LLAC, as will be seen in Section V.




(a) The dynamic mechanism. (b) The LLAC mechanism.

Fig. 3. The load-level-based mechanism vs. the dynamic mechanism.

## IV. The Multilink Analytical Model

The exact solution for blocking probabilities in OBS networks is an NP-complete problem [9]. Therefore, many studies employ a single-link model to calculate blocking probabilities in such networks. The single-link model provides an approximation for the network behavior. This model, however, does not consider that the load offered to core nodes is reduced because of the blocking of bursts along source-destination path. Thus, considering a single-link model to evaluate the performance of mechanisms developed for OBS networks cannot reflect the actual behavior of these mechanisms and also may lead to an overprovisioned network. In this section, we introduce a multilink model for the load-level-based admission control mechanism. The multilink model considers the reduced load fixed-point approximation for OBS networks, without service differentiation, developed by Rosberg *et al.* [9].

We consider a network $\mathcal{N}$ for developing the multilink model. Let $L$ be the number of links in $\mathcal{N}$, $W$ be the capacity of a link in wavelengths, and $R$ be the set of all possible routes in $\mathcal{N}$. Each link $v$ is unidirectional and a route $r$ is an ordered set of links that connects a source node to a destination node. The network $\mathcal{N}$ also employs static routing. In addition, we consider the following assumptions.

- The arrival of bursts belonging to class $i$ at route $r$ is a Poisson process with rate $\lambda_{r,i}$.
- The burst transmission time is exponentially distributed with mean $1/\mu$ for all service classes, where $\mu$ represents the service rate of one wavelength in bursts per unit of time.
- All the wavelengths in all of the $L$ links of $N$ have the same service rate $\mu$.
- A burst, no matter its service class, requires the reservation of only one wavelength for its transmission until it reaches the destination or until it is blocked at one of the nodes of $\mathcal{N}$.
- The number of service classes is $n$.

A link $v$ is modeled as a *M/M/W/W* queue, where $W$ is the link capacity in wavelengths. Each link can be represented as a continuous-time Markov chain. Each Markov chain state $\omega$[1] represents the number of occupied wavelengths in a given time ($\omega = 0, 1, 2, \ldots, W$) and the transition rates are given by the total burst arrival rate offered to $v$, $\Lambda_v(\omega)$, and the service rate $\mu$.

After applying the admission criterion, the burst arrival rate of class $i$ at link $v$, denoted by $\lambda_{i,v}(\omega)$, is a function of the number of occupied wavelengths in $v$. If the load level of class $i$ satisfies the admission criterion of LLAC, bursts of this class are admitted. Otherwise, bursts of class $i$ are blocked. Thus,

$$\lambda_{i,v}(\omega) = \begin{cases} \lambda_{i,v}, & \text{if } \omega < l_i \\ 0, & \text{if } \omega \geq l_i \end{cases} . \quad (3)$$

The burst arrival rate of class $i$ at an OBS node that admits bursts carried in link $v$, $\lambda_{i,v}$, is given by

$$\lambda_{i,v} = \sum_{r \in R} \lambda_{i,r} \prod_{u=1}^{L} (1 - I(u,v,r).B_{i,u}(\rho_{i,u}, l_i, W)), \quad (4)$$

where $\rho_{i,v}$ is the load offered to link $v$ for bursts of class $i$, which is given by $\rho_{i,v} = \lambda_{i,v}/\mu$.

Equation (4) takes into account the reduced-load effect to determine the burst arrival rate of class $i$ offered to link $v$. Let $I(u,v,r)$ be a binary variable. If the links $u, v \in r$ and link $u$ strictly precedes, not necessarily immediately, link $v$ along route $r$, then $I(u,v,r)$ equals one. $I(u,v,r)$ is equal to zero, for any another situation where links $u$ and $v$ do not satisfy the previously presented conditions. The blocking probability of bursts belonging to class $i$ in link $u$ is given by $B_{i,u}(\rho_{i,u}, l_i, W)$.

The total burst arrival rate offered to a link $v$, $\Lambda_v(\omega)$, is equal to the sum of the burst arrival rates of the $n$ service classes at $v$, after verifying the LLAC admission criterion.

[1]For simplicity, we consider $\omega(t) = \omega$.

Then, $\Lambda_v(\omega)$ is given by

$$\Lambda_v(\omega) = \sum_{i=0}^{n-1} \lambda_{i,v}(\omega), \quad \omega = 0, 1, 2, \ldots, W-1. \tag{5}$$

The rate $\Lambda_v(\omega)$ is a function of the number of occupied wavelengths, $\omega$, because the arrival rate of each class $i$ offered to link $v$ depends on the LLAC admission criterion.

We have to derive the flow balance equations to calculate the steady-state probabilities $\pi_\omega$ of each chain state $\omega$ [18]. As the probability of a burst of class $i$ be blocked at link $v$, $B_{i,v}$, is equal to the probability of the chain be in a state $\omega \geq l_i$, where $l_i$ is the load level of class $i$ in the time the burst arrives at $v$, we have

$$B_{i,v}(\rho_{i,v}, l_i, W) = \sum_{\omega=l_i}^{W} \pi_\omega = \sum_{\omega=l_i}^{W} \frac{\frac{1}{\omega!\mu^\omega} \prod_{k=0}^{\omega-1} \Lambda_v(k)}{1 + \sum_{j=1}^{W} \frac{1}{j!\mu^j} \prod_{k=0}^{j-1} \Lambda_v(k)}. \tag{6}$$

Considering the blocking of a burst an independent event, which occurs from a link to other link along a route, the blocking probability of bursts belonging to class $i$ in route $r$, $B_i(r)$, is given by

$$B_i(r) = 1 - \prod_{u \in r}(1 - B_{i,u}(\rho_{i,u}, l_i, W)) \tag{7}$$

and the blocking probability of an arbitrary burst that belongs to class $i$, $B_i$, satisfies

$$B_i = \frac{1}{\alpha_i} \sum_{r \in R} \lambda_{i,r}.B_i(r), \tag{8}$$

where $\alpha_i = \sum_{r \in R} \lambda_{i,r}$.

As we consider the reduced-load effect in the multilink model, there is no exact solution for blocking probability in a given link. An efficient method to calculate the blocking probability of bursts belonging to class $i$ in a link employs a successive iteration procedure [9]. For this purpose, we define a vector $B_i = (B_{i,1}, B_{i,2}, B_{i,3}, \ldots, B_{i,L})$, which represents the blocking probability of bursts of class $i$ in every link of the network. The iteration procedure begins when we assign an initial value for burst blocking probabilities of class $i$ for every link of $N$, resulting in vector $B_i^0$. Then, at each iteration $m$, we solve the blocking probability of class $i$ according to results of iteration $m-1$. To obtain the new vector of blocking probabilities $B_i^m$, we apply a transformation $T(B_i)$ defined by

$$T(B_i) = (T_{i,1}(B_i), T_{i,2}(B_i), T_{i,3}(B_i), \ldots, T_{i,L}(B_i)), \tag{9}$$

where $T_{i,u}(B_i) = B_{i,u}(\rho_{i,u}, l_i, W)$ and $B_i^m = T(B_i^{m-1})$. The iteration procedure is then repeated until $B_i^m$ is sufficiently close to $B_i^{m-1}$. In all scenarios analyzed in this article, no matter the initial vector, the successive iteration procedure always converged to a unique fixed point.

# V. Results

In this section, we compare the proposed load-level based mechanism to the static and dynamic mechanisms. For the static and dynamic mechanisms, we extend the single-link models proposed by Zhang *et al.* [16] also based on the reduced load approximation method. The multilink models for these two mechanisms are not presented for the sake of brevity. The analysis considers two service classes, where class 0 is the high-priority class. The number of wavelengths per link is $W = 16$ and the capacity of each wavelength is 1.0 Gb/s. The mean burst size is 128 kB for all service classes. We consider that the network employs the JET signaling protocol for both simulation and mathematical analysis. The analysis is divided into two parts. First, we verify the accuracy of the multilink model developed for LLAC in comparison with the single-link model. Both models are compared with simulation results. After that, we evaluate the performance of the three mechanisms and the network without any QoS support, referred as classless, according to the load offered to the network and the aggressiveness against the low priority class (class 1).

## A. Accuracy of the Multilink Model

We verify the accuracy of the developed multilink model against simulation results. We consider a chain topology where the source is the first node of the chain and the destination is the last one. The goal of this analysis is to show that the larger the length of the source-destination path and the higher the offered load, the more essential a multilink model becomes to accurately estimate the burst-blocking probability. In the analysis, we compare the multilink model, based on reduced load approximation, to the single-link approximation. The single-link model does not consider that the blocking probability in a link is influenced by other links of the network. Considering the single-link approximation and a chain of nodes, the blocking probability of bursts from a given class $i$ is estimated by

$$B_i = 1 - (1 - B_{i,v})^d, \tag{10}$$

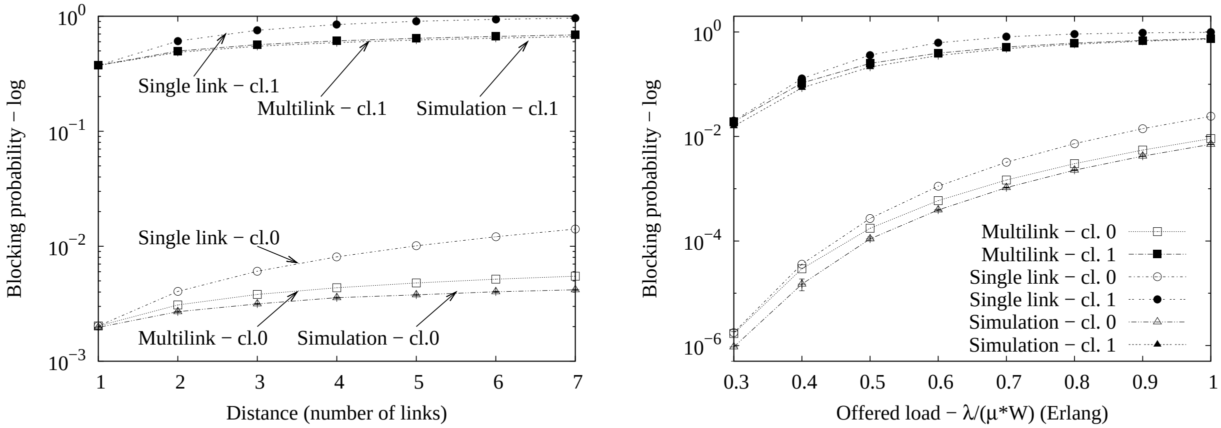
where $B_{i,v}$ is the blocking probability of bursts belonging to class $i$ in a single link $v$ and $d$ is the distance from the source to the destination. We define distance as the number of links that bursts have to traverse.

In this analysis, we apply the two approximation methods to the LLAC mechanism. We compare both to simulation results[2]. We evaluate the accuracy of both models according to the estimation error $e$. This parameter is defined by

$$e(\%) = \frac{v_e - v_s}{v_s} \times 100, \tag{11}$$

where $v_e$ and $v_s$ are, respectively, the estimated value and the simulated value of blocking probabilities. Thus, the larger the error, the lower the accuracy. We have $l_0 = 16$ for class 0 and $l_1 = 12$ for class 1 and 30% of bursts belong to class 0. First, we fixed the load offered to the chain in 0.9 erlangs, in order to analyze the impact of the length of the source-destination path

[2] We develop an event-driven simulator for this purpose.




(a) Impact of the distance between source and destination.

(b) Impact of the offered load.

Fig. 4. Accuracy of single-link and multilink models developed for LLAC.

on blocking probabilities. The distance between the source and the destination ranges from 1 to 7.

According to Fig. 4(a), the larger the distance from the source to the destination, the greater the difference among the estimation errors of each model. For a distance of 3 links, the multilink model provides $e = 20\%$ and $e = 3.3\%$ for classes 0 and 1, respectively. On the other hand, with the single-link model we have much higher estimation errors. For classes 0 and 1, respectively, $e$ is equal to 92% and 38%. In this case, the multilink model provides an estimation error 4.5 times lower than the single-model for class 0 and 11.5 times lower for class 1. For a distance of 7 links, the estimation of the multilink model is even better than the one provided by the single-link model. The multilink model provides an estimation error 7.6 times lower than the single-model for class 0 and 13 times lower for class 1. We have $e = 31\%$ and $e = 3.4\%$ for classes 0 and 1 with the multilink model, respectively, and, $e = 237\%$ and $e = 45\%$ for classes 0 and 1 with the single-link model. The analysis considering the multilink model shows that the performance of LLAC is underestimated when we do not take into account the reduced-load effect. Thus, we conclude that the multilink model estimates the performance of the proposed mechanism better than the single-link model. It is worth mentioning that the reason to the small difference between the simulated and the multilink curves for the blocking probability of class 1 is that a high number of low-priority bursts are blocked by the node nearest to the source (edge node). As a consequence, the load offered by class 1 to the following nodes is extremely reduced. Thus, fewer bursts will be blocked by core nodes in comparison with the edge node. On the other hand, the single-link model does take into account the reduced-load effect. Consequently, the difference between the simulated and the single-link curves for the blocking of class 1 increases more rapidly with the distance.

In order to evaluate the impact of the offered load, the length of the source-destination path is fixed (7 links). The offered load ranges from 0.1 to 1 erlang. Fig. 4(b) ratifies the better estimation of the multilink model. The difference among the estimation errors of each method increases as the load offered to the chain increases The explanation for such difference is similar to the one previously presented. As the offered load increases, more bursts are blocked by edge nodes, and, consequently, fewer bursts are offered to core nodes. Only the multilink model takes this effect into account. For an offered load equal to 0.5 erlangs, the multilink model provides an estimation error 2.5 times lower than the single-model for class 0 and 3.75 times lower for class 1. For an offered load of 1 erlang, these differences increase. With the multilink model, the estimation errors of classes 0 and 1 are, respectively, 8.5 and 11.5 times lower than the ones provided by single-link model. Therefore, we reinforce that the multilink model better estimates the performance of LLAC than the single-link model.

## B. Impact of the Offered Load

The NSFNET network, illustrated in Fig. 5, is used in our analysis. This network is composed of 16 nodes and 50 unidirectional links. The weight assigned to each link is used in the shortest-path computation and represents the length of the links in units of 10 km [19]. The length of the links ranges from 750 to 3000 km.

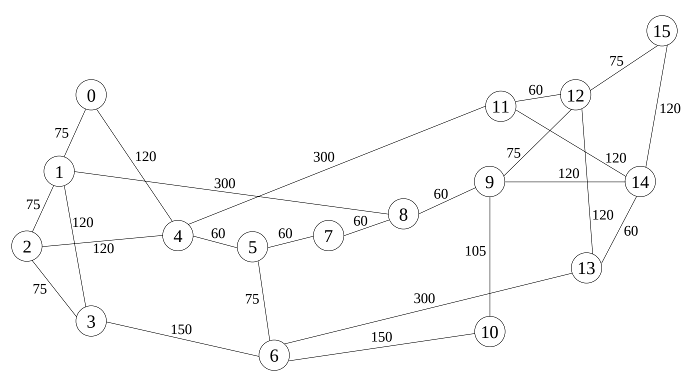
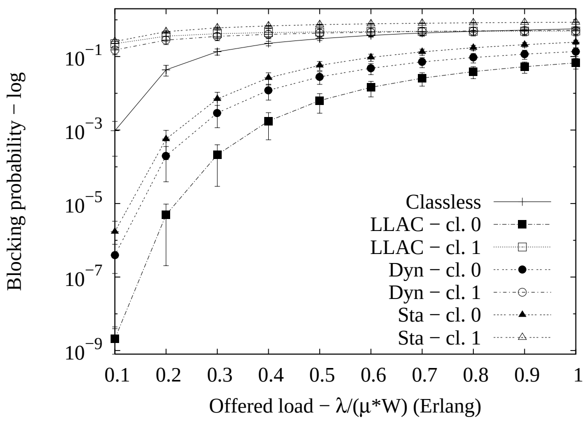
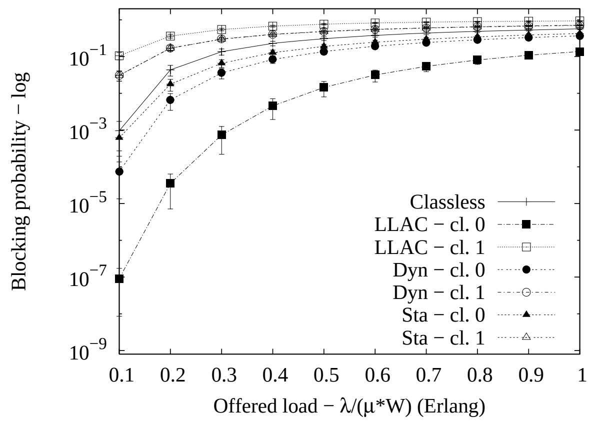


Fig. 5. The NSFNET network.

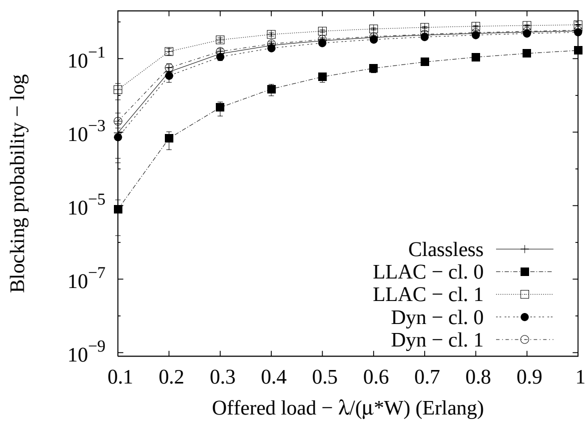
The performance of admission control mechanisms depends




(a) More aggressive configuration.




(b) Intermediary configuration.



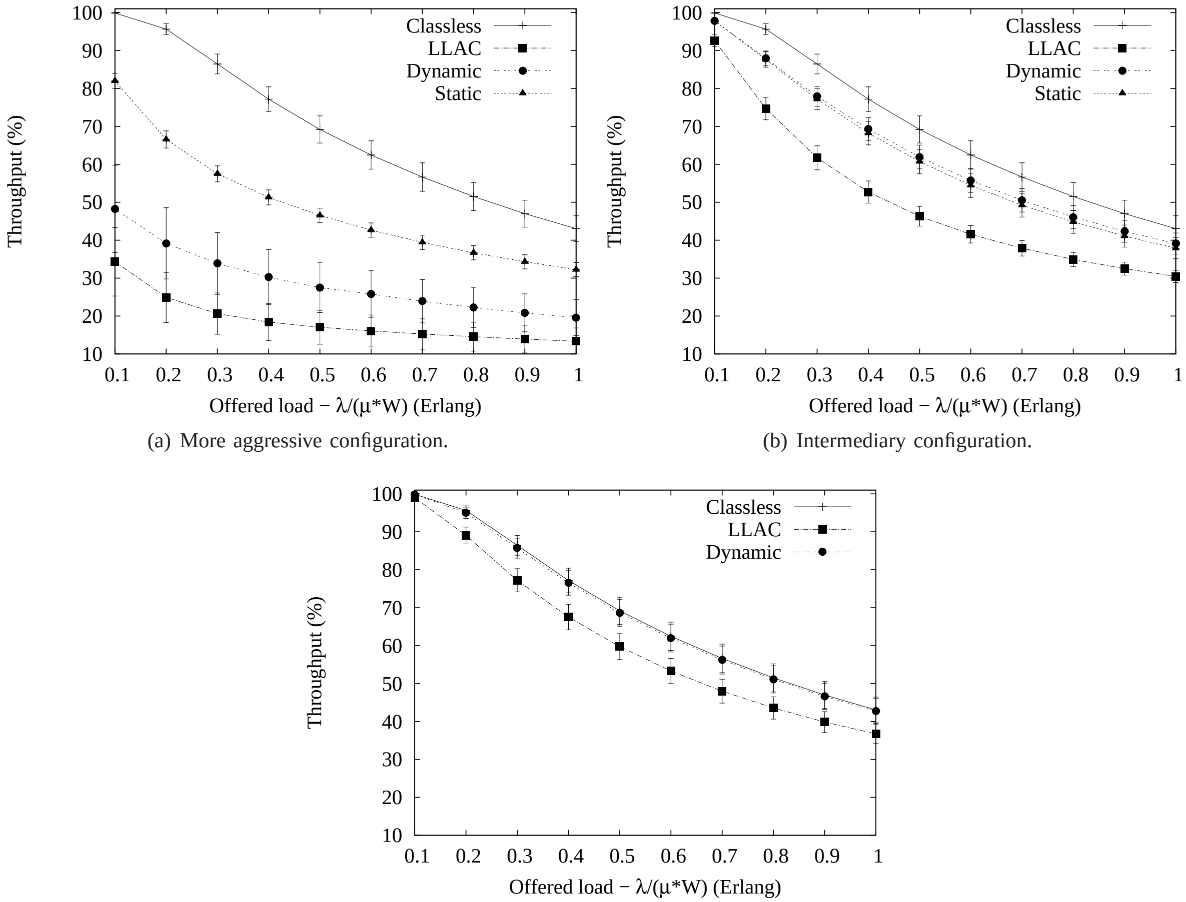

(c) Less aggressive configuration.

Fig. 6. Performance evaluation of the admission control mechanisms: blocking probability vs. offered load.

on the number of burst flows and the source-destination pair of each flow. Hence, for each analysis run, we randomly choose 16 source-destination pairs. We define that each node can be the source of only one flow and thus we assure that each one of the 16 nodes of the network generates bursts. The shortest path for each source-destination pair is computed by Dijkstra's algorithm. A source generates bursts of both service classes and the same set of source-destination pairs are considered for all mechanisms. After computing the routes, the successive iteration procedure is performed to calculate the blocking probability of each service class. First, we compute the reduced load offered to each link. After that, the Tangram-II tool [20] is used to solve the blocking probability of all classes in a given link, according to the model developed in Section IV. The result given by Tangram-II is then used to compute the load offered to each link in the next iteration. This procedure is repeated until the result of the last iteration is sufficiently close to the result of the previous iteration. For every point of the curves presented in this section, we calculated the confidence interval for a 95% confidence level. Error bars are plotted as vertical lines at each point.

In order to evaluate the impact of the offered load on the blocking probability experienced by each service class and also on the network throughput, the traffic amount, per flow, of classes 0 and 1 is fixed. We consider that 30% of bursts belong to the high-priority class, class 0, and 70% belong to class 1. We also assume, for the three mechanisms, the same value for the maximum number of wavelengths that bursts of class 1 can occupy. As a consequence, the three mechanisms reserve the same number of wavelengths for high-priority class: $W_0$ for the static, $W_0 - W_1$ for the dynamic, and $l_0 - l_1$ for the load-level-based mechanism. We analyze three situations of aggressiveness against the low-priority class. For the more aggressive configuration, bursts of class 1 can occupy up to 25% of the wavelengths in each link of the network. For the intermediary configuration, bursts of class 1 can occupy up to 50% of wavelengths. Finally, for the less aggressive configuration, bursts of class 1 can occupy up to 75% of the wavelengths in each link. Table I summarizes the parameters for the three mechanisms. The performance of the static mechanism is not evaluated for the less aggressive configuration, because the number of reserved wavelengths for class 1 would be greater than the one reserved for class 0. Figs. 6 and 7 show, respectively, the burst blocking probability and the network throughput for the three mechanisms and for the classless network.

For the more aggressive configuration, as shown in Fig. 6(a), LLAC provides a lower blocking probability for high-priority




(a) More aggressive configuration.

(b) Intermediary configuration.

(c) Less aggressive configuration.

Fig. 7. Performance evaluation of the admission control mechanisms: blocking probability vs. network throughput.

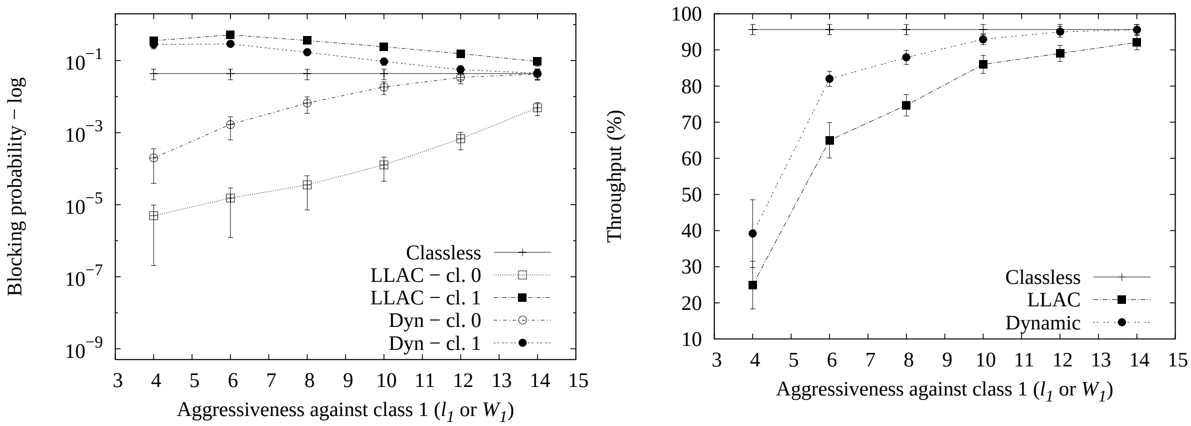
TABLE I
PARAMETERS FOR THE ANALYZED CONFIGURATIONS.

| **Configuration** | **LLAC** ($l_0$ **and** $l_1$) | **Dynamic** ($W_0$ **and** $W_1$) | **Static** ($W_0$ **and** $W_1$) |
|---|---|---|---|
| **More aggressive** | 16 and 4 | 16 and 4 | 12 and 4 |
| **Intermediary** | 16 and 8 | 16 and 8 | 8 and 8 |
| **Less aggressive** | 16 and 12 | 16 and 12 | - |

bursts, as the offered load to the network increases. For an offered load of 0.6 erlangs, the blocking probability of class 0 provided by LLAC is about five times less than the one provided by the static or dynamic mechanisms. For the same offered load, the three mechanisms provide approximately the same blocking probability to bursts of class 1. The better performance of the LLAC mechanism, in comparison with the other two mechanisms, is a consequence of its admission criterion, which takes into account the total number of occupied wavelengths in a link instead of the number of wavelengths occupied by each service class in a link. Because of its criterion, LLAC becomes more aggressive with low-priority bursts and privileges high-priority bursts. With LLAC, the probability that a burst belonging to class 0 finds a wavelength occupied by a burst of class 1, at a time $t$, is small because this mechanism admits a lower number of bursts of class 1. As a consequence, the contention for network resources is, most of the time, between bursts of class 0.

The LLAC mechanism, for the intermediary configuration, is the only one that effectively differentiates the blocking probability experienced by service classes. According to Fig. 6(b), the curves of dynamic and static mechanisms for classes 0 and 1 are close as the offered load increases. Thus, the service differentiation provided by both mechanisms is degraded for higher values of offered load. It is also worth mentioning that, for this configuration, the blocking probability provided by LLAC to bursts of class 1 does not decrease as the offered load increases. As the aggressiveness against class 1 is lower, the number of low-priority bursts blocked by nodes near to the source is not enough to reduce the blocking probability of this class at the following nodes in the path until the destination. Such a fact could not be observed, if a single-link model has been used.

The results for the less aggressive configuration, presented in Fig. 6(c), confirm that LLAC differentiates the blocking probability of each service class despite the reduced aggressiveness against class. For this configuration, the dynamic mechanism does not properly differentiate the blocking probability experienced by classes even when the load offered to the




(a) Blocking probability.

(b) Network throughput.

Fig. 8. Effectiveness of the admission control mechanisms.

network is low. On the other hand, for the same offered load, LLAC provides to bursts of class 0 a blocking probability almost 1000 times less than the one provided to bursts of class 1.

The better differentiation provided by LLAC impacts the network throughput, as shown in Fig 7. For all configurations, the best case is the classless network curve. The throughput, in this case, ranges from 99% to 43% depending on the offered load. For the more aggressive configuration, illustrated by Fig. 7(a), the throughput provided by LLAC ranges from 34% to 13%. The maximum throughput values of dynamic and static mechanism are, respectively, 48% and 82%. The minimum values are 19% and 32%. Thus, we conclude that the more effective the service differentiation provided by a mechanism, the higher the impact on the network throughput. The network throughput provided by each mechanism, however, also depends on the aggressiveness against low-priority bursts. Figs. 7(b) and 7(c) show, respectively, the intermediary and less aggressive configurations. For both configurations, the difference between the throughput provided by LLAC and the one provided by the other mechanisms is reduced. For the less aggressive configuration and an offered load equal to 1 Erlang, for example, LLAC effectively differentiates the services and provides a throughput only 6.3% lower than the one provided by the classless network.

### C. Effectiveness of the Mechanisms

The previous results show that the number of wavelengths reserved for each class impacts the performance of the mechanisms. The larger the number of wavelengths a class can occupy, the lower the blocking probability experienced by this class. Thus, we evaluate the performance of LLAC and the dynamic mechanism in terms of blocking probability and network throughput as the aggressiveness against class 1 decreases. For both mechanisms, bursts of class 0 can occupy any available wavelength ($l_0 = W_0 = 16$). In addition, the load offered to the network is 0.2 erlangs, 30% of bursts belong to class 0, and the number of wavelengths that bursts of class 1 can occupy in a link, $l_1$ or $W_1$, ranges from 4 to 14.

As shown in Fig. 8(a), LLAC remains differentiating the blocking probability of each class as the load level of the class 1, $l_1$, increases. Even when $l_1 = 14$, just two units less than $l_0$, the two service classes experience different blocking probabilities. The blocking probability for class 0 is in order of $10^{-3}$ and for class 1 is in order of $10^{-1}$. In this case, as shown in Fig.8(b), the network throughput with LLAC is equal to 92%, which is only 4% lower than the one achieved by the classless network. These results confirm that is possible to differentiate the blocking probability of each class and to achieve higher network throughput using LLAC, without starving the low-priority traffic. The level of differentiation imposed to the services is a choice of the network operator. On the other hand, the service differentiation provided by the dynamic mechanism is degraded as the parameter $W_1$ increases. If $W_1 = 12$, bursts of both classes experience approximately the same blocking probability. For this configuration, the dynamic mechanism only differentiates the services, if the difference between the parameters $W_0$ and $W_1$ is larger than 4 units. Thus, we conclude that LLAC is less sensitive to the variation of the aggressiveness against low-priority class than the dynamic mechanism.

The number of service classes and also the link capacity impact the performance of LLAC. The proposed mechanism, however, also performs better than the other two mechanisms considering more than two service classes and also more than 16 wavelengths per link. For up to seven classes, we have shown that LLAC properly differentiates the services unlike the static and dynamic mechanisms [8]. In addition, the higher the number of wavelengths per link, the lower the blocking probability experienced by high-priority bursts. On the other hand, this behavior cannot be observed in the blocking probability experienced by bursts of the low-priority class, depending on the aggressiveness against this class. This happens with LLAC and also with the dynamic mechanism, which degrades the service differentiation even for higher link capacities than 16 wavelengths per link. Thus, we conclude that the performance of each mechanism is more impacted by the aggressiveness against each class than by the link capacity [8].

## VI. Conclusion

In this article, we derived a multilink analytical model for the load-level-based admission control mechanism (LLAC). The main goal is to evaluate the performance of LLAC in a real network topology, using the developed multilink model. We verified the accuracy of the multilink model developed for LLAC against simulation results and compared this model with the single-link model. We also evaluated the performance of the proposed mechanism compared with other two similar mechanisms. The blocking probability provided by these mechanisms is calculated according to the load offered to the network and the aggressiveness against low-priority class.

Our results show that the multilink model provides a more accurate blocking probability estimation than the single-link model. Both are compared with simulation results. The multilink model provides an estimation error up to 13 times lower than the one provided by the single-model for the analyzed configurations. Thus, the multilink model estimates the performance of the proposed mechanism better than the single-link model. In addition, the LLAC mechanism, compared with the static and dynamic mechanisms, provides a lower blocking probability to the high-priority bursts in all analyzed configurations. Even when the offered load increases and/or the aggressiveness against the low-priority class decreases, LLAC effectively differentiates the blocking probability experienced by the service classes. This better differentiation leads to the starvation of the low priority-class and lower network throughput in a few situations. The starvation, however, is a choice of the network operator, because LLAC remains differentiating the services for low levels of aggressiveness against the low-priority class. In addition, the less the aggressiveness against low-priority bursts, the higher the network throughput provided by LLAC.

## Acknowledgment

This work has been supported by CNPq, CAPES, FAPERJ, FINEP, RNP and FUNTTEL.

## References

[1] C. Qiao and M. Yoo, "Optical Burst Switching - a new paradigm for an optical Internet," *Journal of High Speed Networks*, vol. 8, no. 1, pp. 69–84, Jan. 1999.

[2] T. Battestilli and H. Perros, "An introduction to optical burst switching," *IEEE Communications Magazine*, vol. 41, no. 8, pp. S10–S15, Aug. 2003.

[3] M. Fawaz, B. Daheb, O. Audouin, M. Du-Pond, and G. Pujolle, "Service level agreement and provisioning in optical networks," *IEEE Communications Magazine*, vol. 42, no. 1, pp. 36–43, Jan. 2004.

[4] X. Liu, C. Qiao, W. Wei, and T. Wang, "A universal signaling, switching and reservation framework for future optical networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 27, no. 12, pp. 1806–1815, June 2009.

[5] B. Martini, V. Martin, F. Baroncelli, K. Torkman, and P. Castoldi, "Application-driven control of network resources in multiservice optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 1, no. 2, pp. A270–A283, July 2009.

[6] A. Ziviani, J. F. de Rezende, and O. C. M. B. Duarte, "Evaluating the expedited forwarding of voice traffic in a differentiated services network," *International Journal of Communication Systems*, vol. 15, no. 9, pp. 799–813, Nov. 2002.

[7] M. Yoo, C. Qiao, and S. Dixit, "QoS performance of optical burst switching in IP-over-WDM networks," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 10, pp. 2062–2071, Oct. 2000.

[8] I. M. Moraes, R. P. Laufer, D. de O. Cunha, and O. C. M. B. Duarte, "An efficient admission control mechanism for optical burst-switched networks," *Photonic Network Communications*, vol. 18, no. 1, pp. 65–76, Aug. 2009, pp. 65–76.

[9] Z. Rosberg, H. L. Vu, M. Zukerman, and J. White, "Blocking probabilities of optical burst switching networks based on reduced load fixed point approximations," in *IEEE INFOCOM*, Mar. 2003.

[10] I. M. Moraes and O. C. M. B. Duarte, "Multilink performance of the load-level-based admission control mechanism for obs networks," in *IEEE International Conference on Communications - ICC*, May 2008, pp. 40–44.

[11] T. Tachibana, "Burst-cluster transmission with probabilistic pre-emption for reliable data transfer in high-performance OBS networks," *Photonic Network Communications*, vol. 17, no. 3, pp. 65–76, Jun. 2009, pp. 245–254.

[12] W. Liao and C.-H. Loi, "Providing service differentiation for optical-burst-switched networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 22, no. 7, pp. 1651–1660, July 2004.

[13] J. Phuritatkul, Y. Ji, and Y. Zhang, "Blocking probability of a preemption-based bandwidth-allocation scheme for service differentiation in OBS networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 24, no. 8, pp. 2986–2993, Aug. 2006.

[14] P. Reviriego, J. A. Hernández, and J. Aracil, "Analysis of average burst-assembly delay and applications in proportional service differentiation," *Photonic Network Communications*, vol. 14, no. 2, pp. 183–197, Oct. 2007.

[15] J. Wan, Y. Zhou, X. Sun, and M. Zhang, "Guaranteeing quality of service in optical burst switching networks based on dynamic wavelength routing," *Optics Communications*, vol. 220, pp. 85–95, Mar. 2003.

[16] Q. Zhang, V. M. Vokkarane, J. P. Jue, and B. Chen, "Absolute QoS differentiation in optical burst-switched networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 9, pp. 2062–2071, Nov. 2004.

[17] L. H. M. K. Costa, S. Fdida, and O. C. M. B. Duarte, "Incremental service deployment using the Hop By Hop multicast routing protocol," *IEEE/ACM Transactions on Networking*, vol. 14, no. 3, pp. 543–556, June 2006.

[18] K. S. Trivedi, *Probability and Statistics with Reliability, Queuing and Computer Science Applications*, 2nd ed. John Wiley & Sons, 2002.

[19] H. Zang, J. P. Jue, L. Sahasrabuddhe, R. Ramamurthy, and B. Mukherjee, "Dynamic lightpath establishment in wavelength-routed WDM networks," *IEEE Communications Magazine*, vol. 39, no. 9, pp. 100–108, Sept. 2001.

[20] E. de Souza e Silva and R. M. M. Leão, "The TANGRAM-II environment," in *XI International Conference on Modelling Tools and Techniques for Computer and Communication System Performance Evaluation - TOOLs*, Mar. 2000, pp. 366–369.

**Igor M. Moraes** (S'08) received the Electronic Engineer degree and the M.Sc. and the D.Sc. degrees in electrical engineering from the Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil, in 2004, 2006, and 2009, respectively. His major research interests are in optical networks, security, wireless networks and peer-to-peer video streaming.

**Otto Carlos M. B. Duarte** received the Electronic Engineer degree and the M.Sc. degree in electrical engineering from the Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil, in 1976 and 1981, respectively, and the Dr. Ing. degree from ENST/Paris, Paris, France, in 1985. Since 1978, he has been a Professor with UFRJ. From January 1992 to June 1993, he was with MASI Laboratory, University Paris 6, Paris. In 1995, he spent three months with the International Computer Science Institute (ICSI), University of California, Berkeley. In 1999 and 2001, he was an Invited Professor with the University Paris 6. His major research interests are in multicast, QoS guarantees, security, and mobile communications.