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FULL-LENGTH ARTICLE

Analysis of wavelength reservation based quality of service differentiation in optical burst switching networks using Markov model

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Abstract With the increased usage of time-critical applications, the need for differentiation among service classes has become a major goal in research communities. Optical burst switching (OBS) is one of the most promising switching technologies to cope with heavy traffic diversity. To satisfy the bandwidth requirement in OBS networks, the recent literature suggests two efficient techniques: one is based on offset time and the other is on wavelength reservation. In this paper, we analyze the wavelength reservation based technique to support a given number of service classes. We describe a Markov model to estimate the blocking probabilities of various service classes. Simulation is conducted at one of the output ports of a core node to validate the model.

1. Introduction

Since the last few years, the Internet is experiencing an exponential growth in IP traffic [1]. With the increased usage of bandwidth sensitive applications such as video conferencing, voice-on-demand and other multimedia applications, this growing trend is expected to continue for many years to come [2]. To meet this overwhelming demand for bandwidth, wavelength division multiplexing (WDM) technology [3] has become an effective choice for the backbone networks. OBS [4,5] is a promising switching paradigm to carry IP traffic over WDM networks. In the context of OBS, the unit of transmission is a burst. The transmission of each burst is preceded by the transmission of a burst header packet (BHP) to reserve wavelength resources for the upcoming data burst. The BHP undergoes O/E/O conversion at intermediate nodes while the data burst is transmitted all-optically. Unlike circuit switching, a source node does not wait for confirmation that an end-to-end connection has been established; instead, it starts transmitting the burst after a delay referred to as offset, following the transmission of the BHP [6]. The value of the offset time should be greater than or at least equal to the total processing delay encountered by the BHP.

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The rest of the paper is structured as follows: In Section 2, we provide a brief overview of the signaling and scheduling protocols in OBS networks. In Section 3, Quality-of-Service (QoS) differentiation mechanisms to satisfy the burst loss probability (BLP) requirements of various service classes are studied. The analytical models for a single class system as well as its generalization to a 2-class and a k-class scenario are presented in Section 4. Analytical results validating the models are given in Section 5. In Section 6, we conclude the paper.

2. Signaling protocols in OBS networks

Signaling specifies the protocol used for handling traffic requests, and its operation determines whether or not the bandwidth resource is efficiently utilized [7]. Several signaling protocols have been proposed for OBS networks. Among these, two most widely used protocols in the literature are Just-Enough-Time (JET) and Just-In-Time (JIT) protocols, both of which use the offset-based signaling technique [8].

Based on the duration of reservation on the wavelength channel, signaling techniques can be categorized as immediate reservation or delayed reservation [9]. In the immediate reservation technique, the channel on which the data burst is due to arrive is reserved immediately after the BHP is processed. On the other hand, in the delayed reservation technique, the channel is reserved only for the duration of the data burst. When the BHP arrives on the control wavelength, it informs the core node about the upcoming burst length, arrival time, and the wavelength used [10]. For example, JIT signaling protocol uses immediate reservation, while the JET signaling protocol adopts delayed reservation. Since the bandwidth is reserved even when there is no burst, the utilization in JIT protocol is poorer compared to JET protocol. JET protocol outperforms JIT protocol in terms of bandwidth utilization and BLP at the expense of increased computational complexity at the core nodes.

In OBS networks with multiple wavelength channels per link, a scheduling algorithm must be implemented to select the channel on which a burst should be forwarded. In general, wavelength scheduling algorithms can be divided into two distinct categories: non-void filling and void filling algorithms. The non-void filling algorithm maintains the latest available unscheduled time on each wavelength and when a new burst arrives it is scheduled on a wavelength such that the void size is minimized. Examples of algorithms in this category include FFUC (First Fit Unscheduled Channel) [11] and LAUC (Latest Available Unscheduled Channel) [12].

On the other hand, void filling algorithms keep track of all the voids on the wavelengths and try to schedule a burst in one of the voids whenever possible. Examples of this category of algorithms are LAUC-VF (Latest Available Unused Channel with Void Filling) [12], PLAUC-VF (Preemptive Latest Available Unused Channel with Void Filling) [13].

The signaling protocol used in an OBS network plays a prominent role in determining the blocking probability for data bursts in that network [14]. For the JIT protocol, the blocking probability can be calculated by modeling the output port as a $M/G/k/k$ queue, and using the well-known Erlang's B formula for the loss probability:

$$B(\rho, W) = \frac{(\rho)^k/k!}{\sum_{c=1}^{k}(\rho)^c/c!} \tag{1}$$

In this equation, k is the number of wavelengths, and ρ is the offered load. For the JIT protocol, the offered load is $\lambda(b + a)$, where λ is the mean burst arrival rate, a is the burst offset-time in time units, and b is the burst duration in time units. Erlang's B formula has also been used to approximate the blocking probability for the JET protocol by treating the output port as a traditional loss system with an offered load of λb.

3. QoS differentiation in OBS networks

Burst loss due to contention is a major concern in OBS networks. Such contention losses can heavily degrade the performance of OBS networks. Contention occurs when two or more bursts intend to take the same output port, on the same wavelength, at the same time. OBS is a buffer-less technology and OBS networks belong to the class of loss networks [15,16]. The lack of efficient optical buffers makes the task of designing QoS differentiation mechanisms for OBS networks even more important when contention for resources leads to burst loss. The key idea of QoS differentiation mechanism is to allocate more resources to higher priority classes compared to lower priority classes. The wavelength reservation based QoS differentiation mechanism is studied in the literature under the following two alternatives.

3.1. Offset time based approach

The logical explanation of this approach [17,18] is that if the offset time is relatively large, then bandwidth will be reserved before other bursts have a chance to make a reservation. To achieve a certain degree of isolation from lower-priority bursts, an additional offset time is provided to bursts belonging to higher priority classes. A big advantage of this approach is that it is implemented only at the OBS ingress edge nodes and no modifications in the core of the network are required.

To make a tractable analysis, we consider a system with a single switch and a single output port. For instance, we consider two classes of traffic, namely *class 1 (higher priority traffic)*, and *class 0 (lower priority traffic)*. To ensure a higher priority for wavelength reservation, an additional offset time, denoted by T_{offset} is given to class 1 traffic. We denote by t_{ai} and t_{si} the arrival time and the service time for class i (i = 0, 1) traffic respectively. Let l_i denote the average burst length of class i (i = 0, 1) traffic. We refer to Fig. 1 where a burst request from class 0 arrives, followed by a burst request from class 1 traffic. Though $t_{a1} < t_{s0} + l_0$, the blocking of class 1 request can be avoided by selecting a proper T_{offset} such that the condition $t_{a1} + T_{offset} > t_{s0} + l_0$ holds. Thus, T_{offset} needs to be larger than the average burst length of class 0 traffic to avoid blocking of a class 1 burst by a class 0 burst.

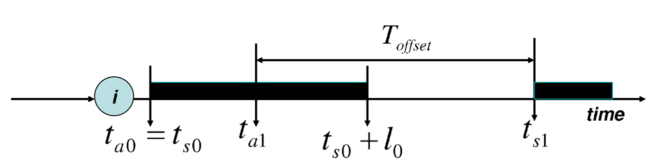

Figure 1 Additional offset time for class 1 traffic.

Consider Fig. 1 when the condition $t_{a1} \cong t_{s0}$ holds. Assuming the burst length is exponentially distributed with an average of l_0, the probability P that a burst in class 1 avoids being blocked by a class 0 burst is given by the following:

$$P(l_0 \leqslant T_{offset}) = 1 - e^{-\frac{T_{offset}}{l_0}} \Rightarrow T_{offset} = -l_0 \ln(1 - P) \tag{2}$$

We plot the above stated probability distribution function (PDF) denoted by P against the ratio of T_{offset} over l_0 in Fig. 2. From the plot it is observed that an additional offset time equal to five times the average burst length of the lower class ensures over 99% of class isolation.

3.2. Wavelength reservation based approach

In this approach [19], more wavelength resources are allocated to higher priority bursts compared to the lower priority bursts according to a threshold parameter. In a 2-class system, the lower priority bursts are discarded when the occupancy of associated resources exceeds the threshold whereas the higher priority bursts are admitted as long as one of the wavelengths is free.

In general, in a multi class system, each traffic class i; $i = 1, 2, 3, \ldots P$ is characterized by a worst-case end-to-end BLP guarantee denoted by B_i^{e2e}. The higher class bursts have more stringent BLP requirements than lower class bursts. In order to attain this objective, the network nodes need to employ appropriate policies to allocate wavelength resources to bursts of each class based on its load and worst-case end-to-end BLP requirement [20,21].

For the purpose of analysis, we assume that the output port of an optical switch consists of W parallel wavelengths, and carries P classes of bursts. The wavelength allocation policy imposes a pair of bounds to each class i, denoted by (W_i^{max}, W_i^{min}) where W_i^{max} is referred to as wavelength upper bound for class i and W_i^{min} is referred to as wavelength lower bound for class i respectively. In a complete wavelength sharing policy, the wavelength bounds for the traffic classes are stated as follows:

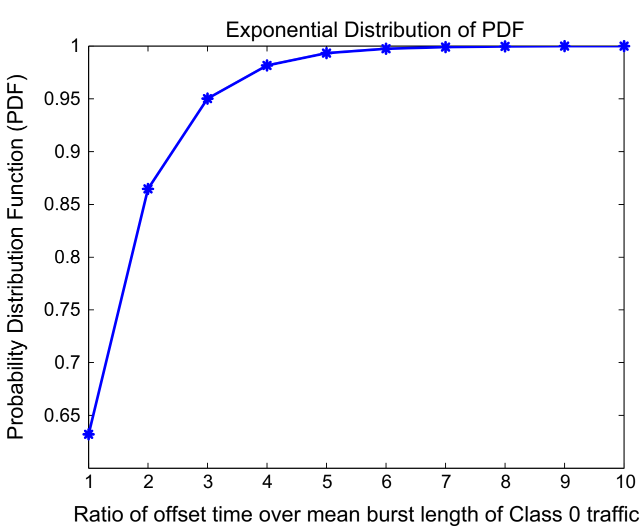

Figure 2 Exponential distribution of PDF.

$$W_i^{min} = 0;\ W_i^{max} = W;\ i = 1, 2, 3, \ldots P \tag{3}$$

In case of a wavelength partitioning (WP) policy, the wavelength space is partitioned among the P traffic classes and each class has a dedicated access to a subset of W wavelengths [22]. Thus, the wavelength bounds for the traffic classes are stated as follows:

$$0 < W_i^{max} = W_i^{min} = W_i < W;\ i = 1, 2, 3, \ldots P$$
$$\sum_{i=1}^{P} W_i = W \tag{4}$$

At last, the family of generalized wavelength sharing (GWS) policies are examined. GWS not only reserves W_i^{min} number of wavelengths to be used exclusively by class i bursts, but also restricts the number of wavelengths that can be occupied simultaneously by class i bursts to W_i^{max}. The wavelength lower and upper bounds for each class are defined as follows:

$$0 \leqslant W_i^{min} < W_i^{max} \leqslant W;\ i = 1, 2, 3, \ldots P \tag{5}$$

To facilitate sharing of wavelengths among the traffic classes, the following constraints are imposed on the wavelength lower and upper bounds:

$$\sum_{i=1}^{P} W_i^{min} < W$$
$$\sum_{i=1}^{P} W_i^{max} > W \tag{6}$$

Let a new class i burst arrives the output port at state $(n_1, n_2, \ldots, n_P)$ where n_i is the number of wavelengths busy in serving class i bursts. Then, the new class i burst can be accommodated on any free wavelength if the following condition holds the following:

$$n_i < \min\left\{ W_i^{max}, W - \sum_{k \neq i} \max\{n_k, W_k^{min}\} \right\} \tag{7}$$

else the burst is dropped.

4. Analytical model

Markov Decision Processes (MDP) are the fundamental aspects to analyze stochastic systems [23]. In this section, we present a Markov model for a single class OBS system that employs wavelength reservation based QoS mechanism as shown in Fig. 3. We consider a single switch and one of its output ports that carries W wavelengths. Further, we assume that there is no use of fiber delay lines (FDLs).

For the above depicted Markov model, we denote a random variable $X(t)$ that defines the number of wavelengths busy in serving class k bursts at time instant t. Let λ_k and μ_k denote the arrival and the service rate of traffic class k. The above continuous time Markov model is a one dimensional birth and death process, and follows the following postulates:

$$P_{ij}(t) = P\{X(t+h) = j | X(h) = i\}$$
$$P_{i(i+1)}(h) = \lambda_k h + o(h);\ h \to 0$$
$$P_{i(i-1)}(h) = i\mu_k h + o(h);\ h \to 0$$
$$P_{ii}(h) = 1 - (\lambda_k + i\mu_k)h + o(h);\ h \to 0$$

According to the above postulates, we can state that:

$$
\begin{aligned}
P_{ij}(t+h) &= P\{X(t+h+u)=j|X(u)=i\} \\
&= P\{X(t+h+u)=j,\, X(t+u)=c;\, c=0,1,\ldots,W|X(u)=i\} \\
&= \sum_{c=0}^{W} P\{X(t+h+u)=j,\, X(t+u)=c|X(u)=i\} \\
&= \sum_{c=0}^{W} P\{X(t+u)=c|X(u)=i\}\, P\{X(t+h+u)=j|\, X(t+u)=c, X(u)=i\} \\
&= \sum_{c=0}^{W} P\{X(t+u)=c|X(u)=i\}\, P\{X(t+h+u)=j|\, X(t+u)=c\} \\
&= \sum_{c=0}^{W} P_{ic}(t)P_{cj}(h) \\
&= P_{i(j-1)}(t)P_{(j-1)j}(h) + P_{ij}(t)P_{jj}(h) + P_{i(j+1)}(t)P_{(j+1)j}(h) + \sum_{c\neq j,j-1,j+1} P_{ic}(t)P_{cj}(h) \\
&= P_{i(j-1)}(t)[\lambda_k h + o(h)] + P_{ij}(t)[1-(\lambda_k + j\mu_k)h + o(h)] + P_{i(j+1)}(t)[(j+1)\mu_k h + o(h)] + o(h) \\
&= \lambda_k h P_{i(j-1)}(t) + P_{ij}(t) - (\lambda_k + j\mu_k)hP_{ij}(t) + (j+1)\mu_k h P_{i(j+1)}(t) + o(h) \\
&\Rightarrow\ P_{ij}(t+h) - P_{ij}(t) = \lambda_k h P_{i(j-1)}(t) - (\lambda_k + j\mu_k)hP_{ij}(t) + (j+1)\mu_k h P_{i(j+1)}(t) + o(h) \\
&\Rightarrow\ \frac{P_{ij}(t+h) - P_{ij}(t)}{h} = \lambda_k P_{i(j-1)}(t) - (\lambda_k + j\mu_k)P_{ij}(t) + (j+1)\mu_k P_{i(j+1)}(t) + \frac{o(h)}{h} \\
&\Rightarrow\ P'_{ij}(t) = \lambda_k P_{i(j-1)}(t) - (\lambda_k + j\mu_k)P_{ij}(t) + (j+1)\mu_k P_{i(j+1)}(t);\ h \to 0 \\
&\Rightarrow\ P'_{i0}(t) = -\lambda_k P_{i0}(t) + \mu_k P_{i1}(t)
\end{aligned}
$$

At steady state, $\lim_{t\to\infty} P_{ij}(t) = P_j$ and $\lim_{t\to\infty} P'_{ij}(t) = 0$.

Hence, at steady state the above derivation can be restated as follows:

$$
\begin{aligned}
&-\lambda_k P_0 + \mu_k P_1 = 0 \\
&\Rightarrow\ P_1 = \frac{\lambda_k}{\mu_k} P_0 = \frac{\rho_k^1}{1!} P_0
\end{aligned} \tag{8}
$$

where ρ_k is the traffic intensity of class k.

$$\lambda_k P_{j-1} - (\lambda_k + j\mu_k)P_j + (j+1)\mu_k P_{j+1} = 0;\ j \geqslant 1 \tag{9}$$

From Eqs. (8) and (9), it can be derived that:

$$P_2 = \frac{\rho_k^2}{2!} P_0$$

$$P_3 = \frac{\rho_k^3}{3!} P_0$$

In general, $P_W = \frac{\rho_k^W}{W!} P_0$.

It is intuitive that the probabilities of all possible states of the above Markov model sum up to 1. Hence,

$$
\begin{aligned}
&\sum_{s=0}^{W} P_W = 1 \\
&\Rightarrow\ P_0 = \frac{1}{\frac{\rho_k^0}{0!} + \frac{\rho_k^1}{1!} + \frac{\rho_k^2}{2!} + \cdots + \frac{\rho_k^W}{W!}}
\end{aligned} \tag{10}
$$

From Eq. (10), we observe that the probability of being in state 0 denoted by P_0 decreases with the increase in traffic intensity. The numerical results are verified with $W = 8, 16, 24$ and 32 respectively as shown in Fig. 4.

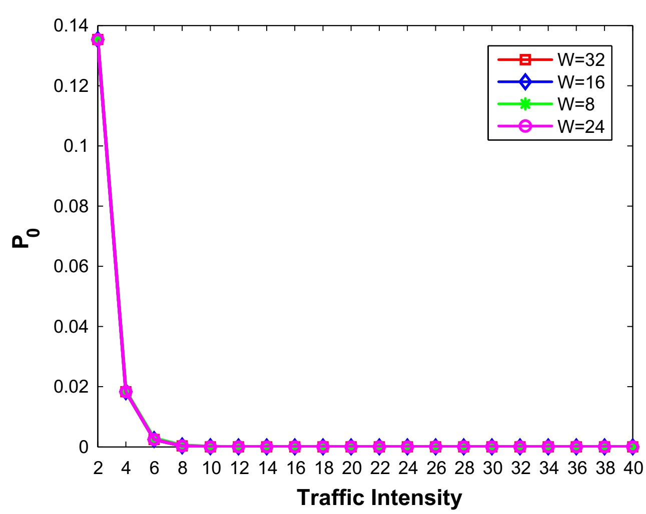

Figure 4 Validation of Eq. (10).

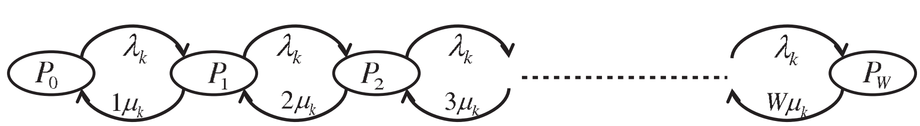

Figure 3 The Markov model for a single class OBS system.

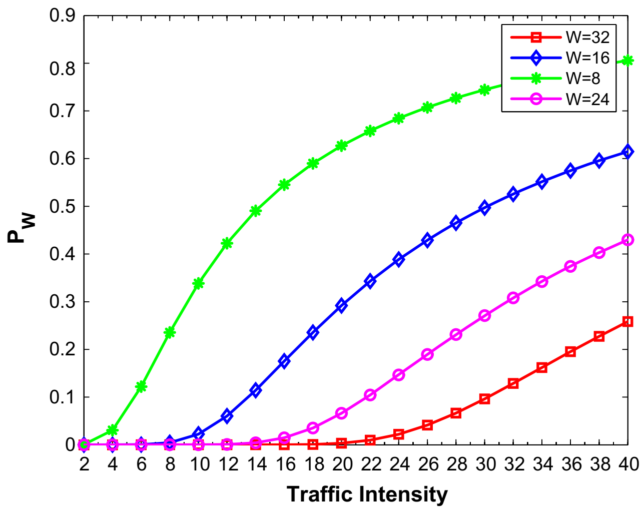

Figure 5 Blocking probability of burst.

A forthcoming burst will be blocked when all the wavelengths are busy and its blocking probability is calculated by the probability of being in state W, denoted by P_W. The blocking probability of a burst increases with the increase in traffic intensity for a given W as shown in Fig. 5. P_W increases with the decrease in W for a given traffic intensity because the output port saturates early for a lower W.

4.1. The 2-class model

A preliminary version of the 2-class Markov model is presented in [1]. However, in this paper, the description of the model has been improved through hand traced examples used to substantiate the stated mathematical equations.

4.1.1. Assumptions

- There are two traffic classes namely Low (L) and High (H) with burst arrival rates λ_1 and λ_2 respectively.
- Each output port consists of W wavelengths where bursts from class L traffic are allowed to use at most W_S wavelengths at any given time. Accordingly, the pair of wavelength lower and upper bounds for class L traffic is $(0, W_S)$ and for class H traffic is $(0, W)$ respectively.

Without loss of generality, the aforementioned assumptions can be used to model a two dimensional birth and death process as shown in Fig. 6. A state of the system at time instant t can be characterized by the pair (n_1, n_2) where n_1 and n_2 are the number of wavelengths assigned to the bursts of classes L and H respectively. According to the above assumptions, $n_1 \leqslant W_S$ and $n_1 + n_2 \leqslant W$.

Let P_{ij} denotes the steady state probability of assigning i and j wavelengths to the bursts of class L and class H respectively and is stated as below:

$$P_{ij} = \frac{\rho_1^i}{i!}\frac{\rho_2^j}{j!}P_{00};\ 0 \leqslant i \leqslant W_S,\ 0 \leqslant j \leqslant W - i \tag{11}$$

where

$$P_{00} = \frac{1}{\sum_{i=0}^{W_S}\sum_{j=0}^{W-i}\frac{\rho_1^i}{i!}\frac{\rho_2^j}{j!}} \tag{12}$$

$$\rho_k = \frac{\lambda_k}{\mu_k} \tag{13}$$

λ_k and μ_k respectively denote the arrival and the service rate of traffic class $k = 1, 2$.

A burst from class H is lost when it finds all wavelengths are busy in serving the already scheduled bursts. Let P_H denotes the BLP associated with class H and is stated as below:

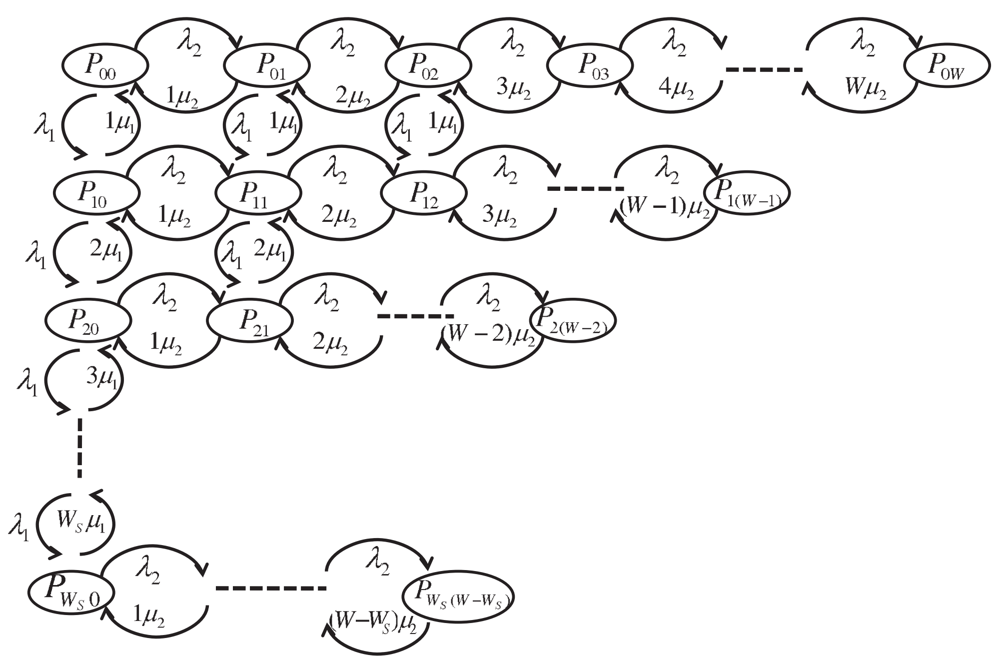

Figure 6 The 2-class Markov model.

$$P_H = \frac{P_{00}}{W!}\sum_{j=W-W_s}^{W} W!\frac{\rho_1^{W-j}}{(W-j)!}\frac{\rho_2^j}{j!} = \frac{P_{00}}{W!}\sum_{j=W-W_S}^{W}\binom{W}{j}\rho_1^{W-j}\rho_2^j \tag{14}$$

Considering the case where both classes are equally prioritized, i.e. $W_S = W$, Eq. (14) can be restated as below:

$$P_{Shared} = (\rho_1+\rho_2)^W \frac{P_{00}}{W!} \tag{15}$$

A burst from class L is lost not only when all the wavelengths are busy in serving the already scheduled bursts but also when the bursts of class L scheduled in the system have reached the threshold limit i.e. W_S. Let P_L denotes the BLP associated with class L and is stated as below:

$$P_L = P_{00}\left[\frac{1}{W!}\sum_{j=W-W_S}^{W}\binom{W}{j}\rho_1^{W-j}\rho_2^j + \frac{\rho_1^{W_s}}{W_S!}\sum_{j=0}^{W-W_S-1}\frac{\rho_2^j}{j!}\right] \tag{16}$$

Let P_T denotes the overall BLP of both the classes at the output port and is stated as below:

$$P_T = \frac{\lambda_1}{\lambda_1+\lambda_2}P_L + \frac{\lambda_2}{\lambda_1+\lambda_2}P_H \tag{17}$$

To examine the above formulas, we consider an exemplary 2-class Markov model as shown in Fig. 7. Let $W = 5$ and $W_S = 2$. In this 2-class exemplary model, the steady state blocking probabilities of bursts from both the classes are estimated in Eqs. (18) and (19) respectively:

$$\begin{aligned} P_H &= \sum_{\substack{i+j\leqslant W\\ i\leqslant W_S}} P_{ij} = P_{05} + P_{14} \\ &\quad + P_{23} = P_{00}\left\{\frac{\rho_1^0}{0!}\cdot\frac{\rho_1^5}{5!} + \frac{\rho_1^1}{1!}\cdot\frac{\rho_1^4}{4!} + \frac{\rho_1^2}{2!}\cdot\frac{\rho_1^3}{3!}\right\} \\ &= \frac{P_{00}}{5!}\sum_{j=3}^{5} 5!\frac{\rho_1^{5-j}}{(5-j)!}\frac{\rho_2^j}{j!} = \frac{P_{00}}{5!}\sum_{j=3}^{5}\binom{5}{j}\rho_1^{5-j}\rho_2^j \end{aligned} \tag{18}$$

$$\begin{aligned} P_L &= P_{05} + P_{14} + P_{23} + P_{20} + P_{21} + P_{22} \\ &= \frac{P_{00}}{W!}\sum_{j=3}^{5} W!\frac{\rho_1^{5-j}}{(5-j)!}\frac{\rho_2^j}{j!} + P_{00}\frac{\rho_1^2}{2!}\sum_{j=0}^{2}\frac{\rho_2^j}{j!} \end{aligned} \tag{19}$$

Given

$$P_{00} = \frac{1}{\sum_{i=0}^{2}\sum_{j=0}^{5-i}\frac{\rho_1^i}{i!}\frac{\rho_2^j}{j!}} \tag{20}$$

In the case of a classless system as modeled in Fig. 8, the bursts from both the classes are equally prioritized. The steady state blocking probability of a burst in such a system is estimated in Eq. (21)

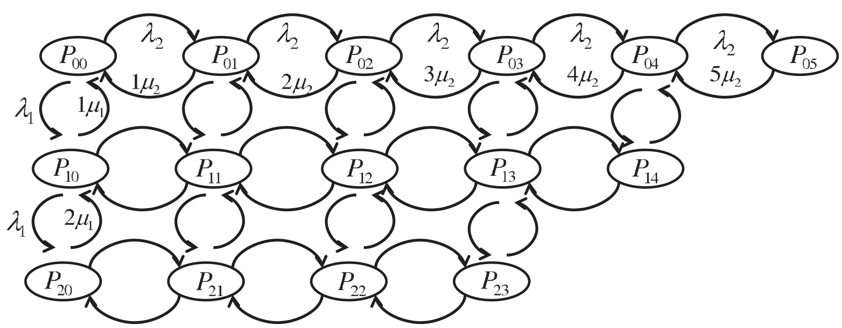

Figure 7 An exemplary 2-class model.

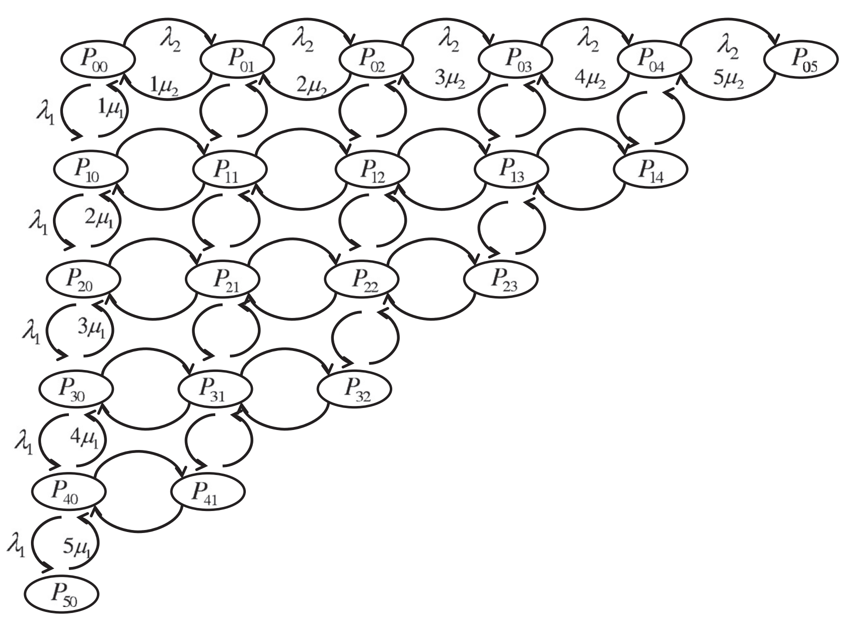

Figure 8 An exemplary classless model.

$$
\begin{aligned}
P_{Shared} &= P_{05} + P_{14} + P_{23} + P_{32} + P_{41} + P_{50} \\
&= \frac{P_{00}}{5!}\left\{5!\frac{\rho_1^0}{0!}\frac{\rho_2^5}{5!} + 5!\frac{\rho_1^1}{1!}\frac{\rho_2^4}{4!} + 5!\frac{\rho_1^2}{2!}\frac{\rho_2^3}{3!} + 5!\frac{\rho_1^3}{3!}\frac{\rho_2^2}{2!}\right. \\
&\quad \left. +5!\frac{\rho_1^4}{4!}\frac{\rho_2^1}{1!} + 5!\frac{\rho_1^5}{5!}\frac{\rho_2^0}{0!}\right\} \\
&= \frac{P_{00}}{5!}\left\{\binom{5}{0}\rho_1^0\rho_2^5 + \binom{5}{1}\rho_1^1\rho_2^4 + \binom{5}{2}\rho_1^2\rho_2^3 + \binom{5}{3}\rho_1^3\rho_2^2\right. \\
&\quad \left. +\binom{5}{4}\rho_1^4\rho_2^1 + \binom{5}{5}\rho_1^5\rho_2^0\right\} = \frac{P_{00}}{5!}(\rho_1 + \rho_2)^5 \qquad (21)
\end{aligned}
$$

4.2. Generalization to k-class model

In this section, we generalize the 2-class model to support an arbitrary number of service classes ($k \geqslant 2$). Let λ_i and μ_i denote, respectively, the arrival and service rate of bursts of some class i ($0 \leqslant i \leqslant k-1$). Without loss of generality, the

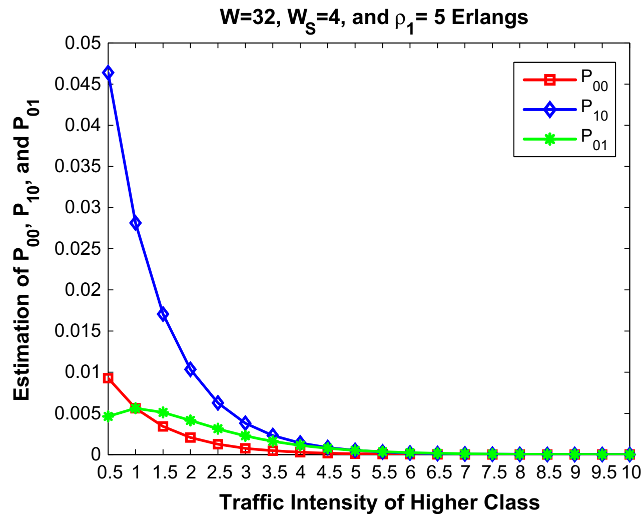

Figure 11 Validation of Eq. (11).

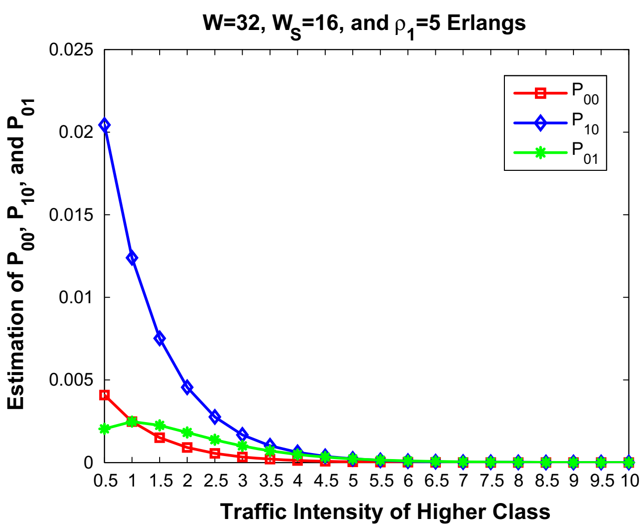

Figure 9 Validation of Eq. (11).

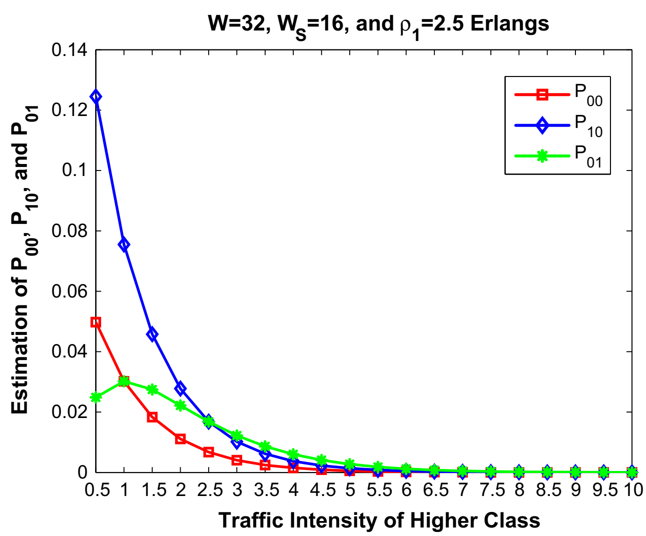

Figure 12 Validation of Eq. (11).

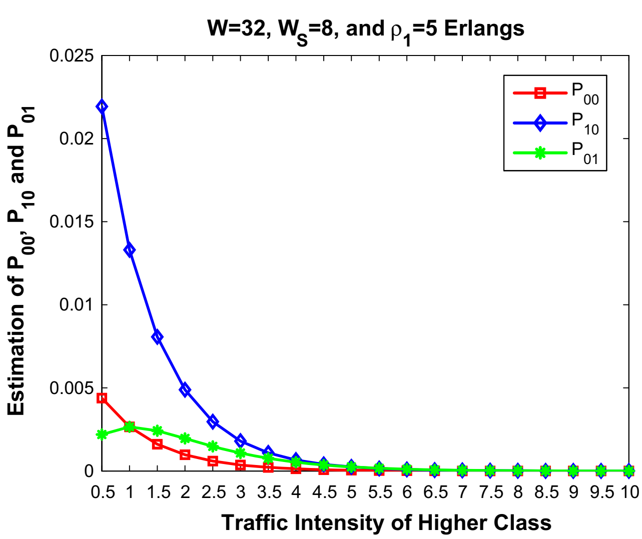

Figure 10 Validation of Eq. (11).

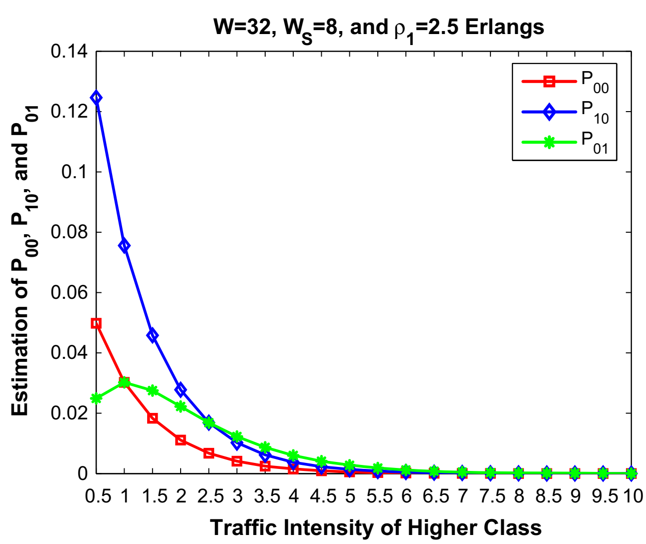

Figure 13 Validation of Eq. (11).

steady state probability of the k-tuple $(n_0, n_1, n_2, \ldots, n_{k-1})$ is given by the following:

$$P_{n_0\, n_1\, n_2,\ldots,n_{k-1}} = \prod_{j=0}^{k-1} \frac{(\rho_j)^{n_j}}{n_j!} P_{(0\,0\,0\ldots k\ times)}; \ n_j \leqslant L_j, \ \sum_{j=0}^{k-1} n_j \leqslant L_{k-1} \tag{22}$$

where L_j is the maximal number of wavelengths allocated to class j.

$$P_{(0\,0\,0\ldots k\ times)} = \sum_{n_0=0}^{\gamma_0} \sum_{n_1=0}^{\gamma_1} \cdots\cdots \sum_{n_{k-1}=0}^{\gamma_{k-1}} \prod_{j=0}^{k-1} \frac{(\rho_j)^{n_j}}{n_j!}; \ 0 \leqslant \gamma_j \leqslant L_j \tag{23}$$

A burst of class S_j fails to get a free wavelength if it either finds, at the instant of arrival, all wavelengths are busy or the maximal number of wavelengths allocated to class S_j has already reached the threshold L_j. Hence, the associated probability is stated as follows:

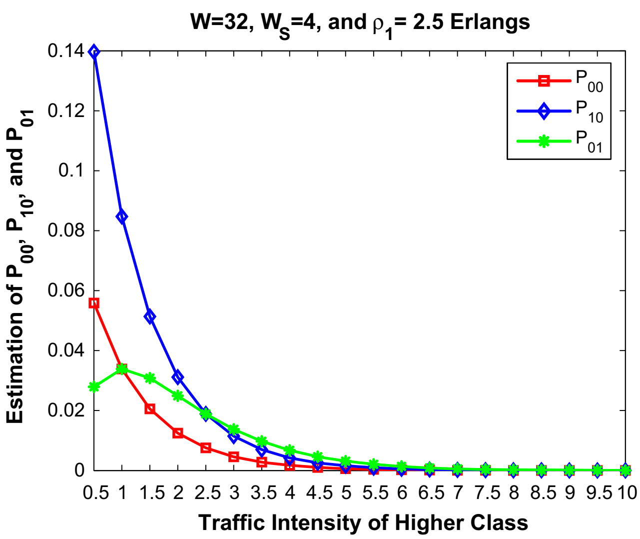

Figure 14 Validation of Eq. (11).

$$P^j = \sum_{\sum_{j=0}^{k-1} n_j = L_{k-1} | n_j = L_j} \prod_{j=0}^{k-1} \frac{(\rho_j)^{n_j}}{n_j!} P_{(0\,0\,0\ldots k\ times)} \tag{24}$$

5. Numerical results & discussion

In this section, we present the analytical results to validate the formulas stated in the preceding section. A single optical switch with one output port and Poisson traffic arrival is considered for different traffic loads. The simulation is verified in a Pentium(R) 4 CPU with a clock cycle of 3.2 GHz and a 2 GB of RAM. The simulator used is MATLAB 7.0.1. In our simulation, the traffic intensity of the shared system is equal to the

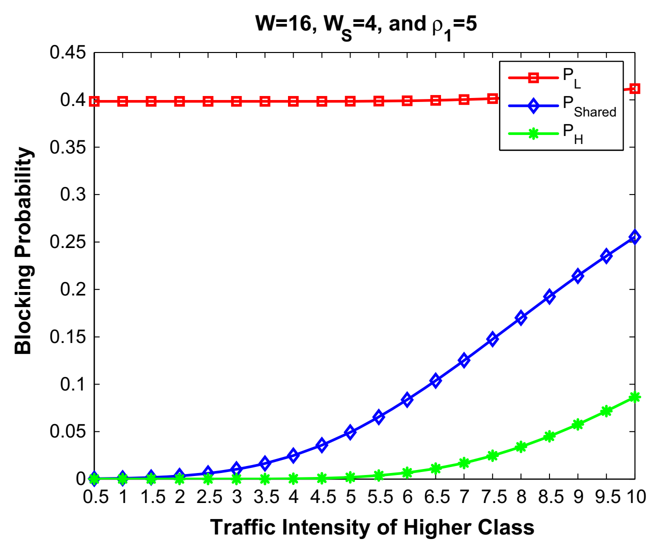

Figure 16 BLP comparison of class L, class H, and shared systems.

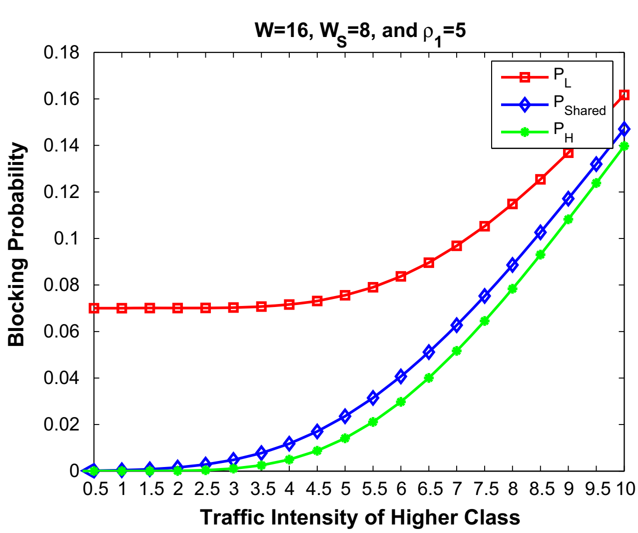

Figure 15 BLP comparison of class L, class H, and shared systems.

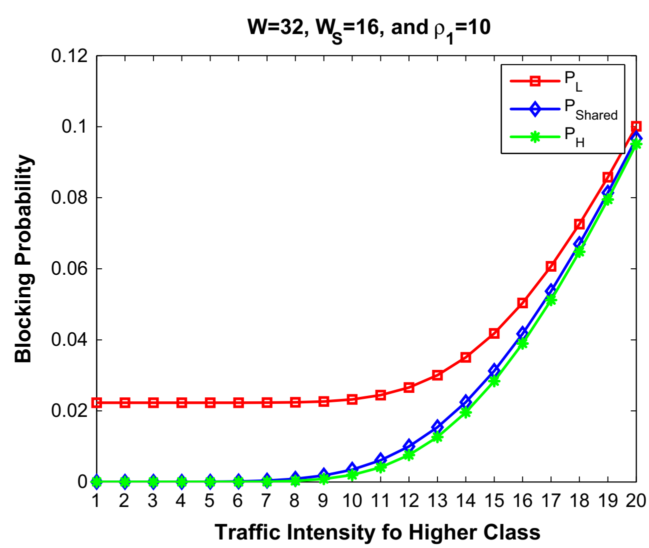

Figure 17 BLP comparison of class L, class H, and shared systems.

sum of the traffic intensities of both class L and class H, i.e. $\rho = \rho_1 + \rho_2$ and the whole wavelength space is allocated to this traffic intensity.

Figs. 9–14 validate Eq. (11) for a given W, W_S and ρ_1. It is observed that with increase in higher class traffic intensity ρ_2, the probability of being in state $(1,0)$ decreases.

In Figs. 15–18, we study the effect of increasing the traffic intensity of class H on the BLP of both class L and the shared system for a given W, W_S and ρ_1. It is observed that class H bursts suffer lesser loss compared to class L bursts. Blocking probabilities of both class L and class H increase as ρ_2 increases. In order to demonstrate service class isolation, P_{Shared} is also depicted as a function of ρ_2. It is observed that P_{Shared} lies between P_H and P_L, implying that bursts of class H are prioritized to those of class L.

In Figs. 19 and 20, we have studied the impact of increasing the traffic intensity of class L on the BLP of class H for a given W and W_S respectively. It is observed that the blocking probability of class H bursts increases with the increase in ρ_1. It is because a class H burst has a lower chance of using the spared wavelengths from the pool of wavelengths allocated to class L when ρ_1 is sufficiently large.

In Figs. 21 and 22, we have studied the impact of W_S on the BLP of class H for a given W and ρ_1 respectively. It is observed that the blocking probability of class H bursts increases with the increase in W_S. When class L is privileged with more number of wavelengths and with the increase in class L traffic, a burst from class H lessens its chance of getting a free wavelength.

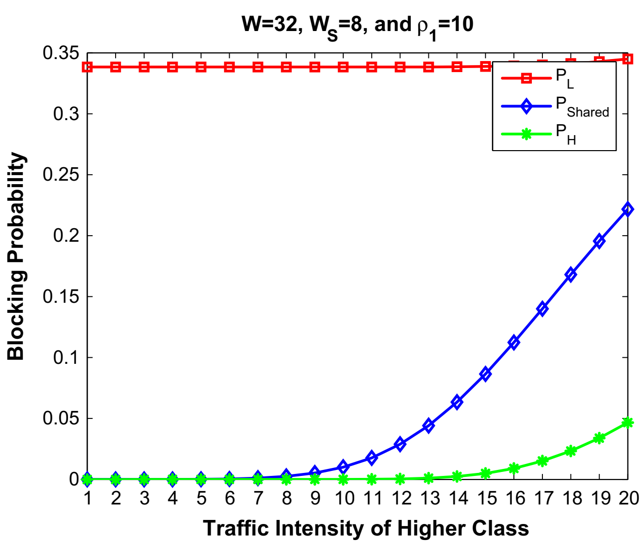

Figure 18 BLP comparison of class L, class H, and shared systems.

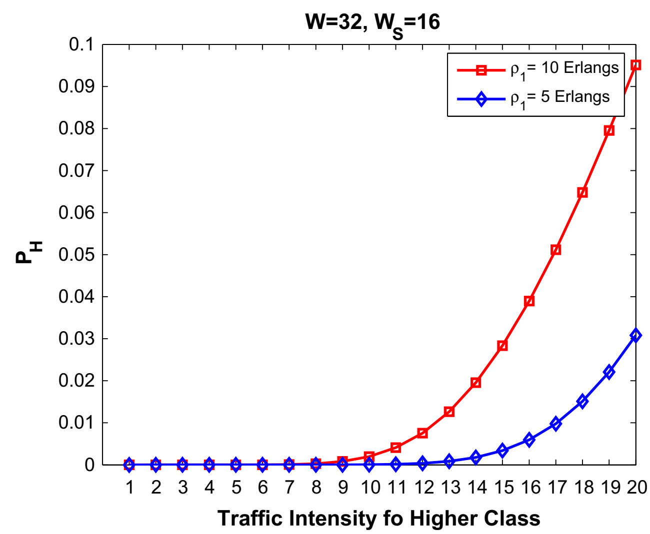

Figure 20 BLP of class H traffic.

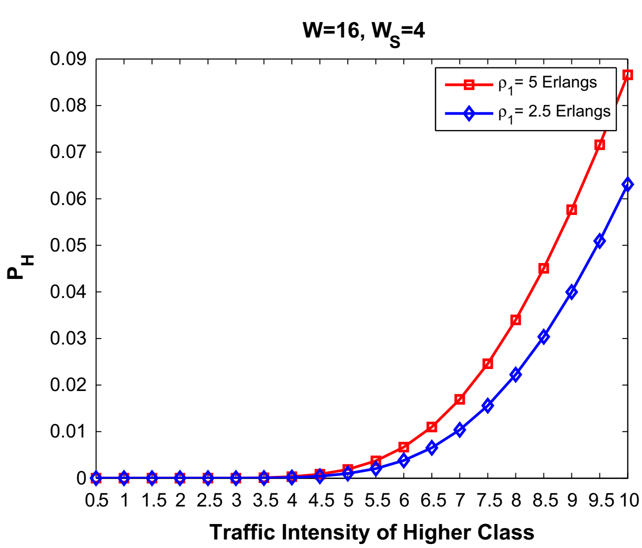

Figure 19 BLP of class H traffic.

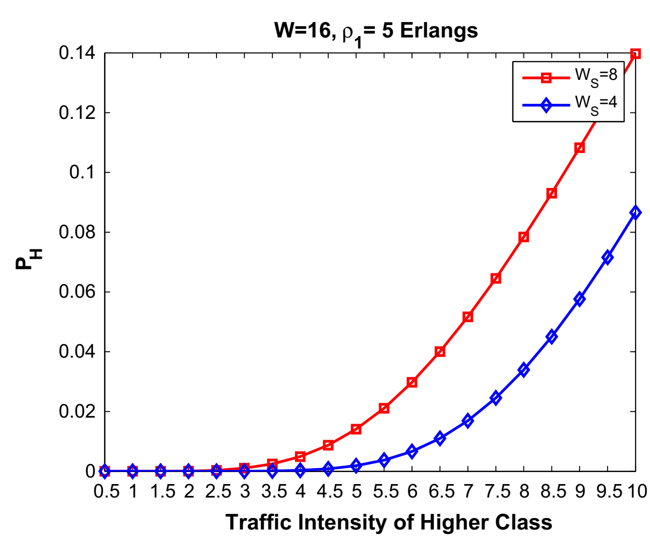

Figure 21 BLP of class H traffic.

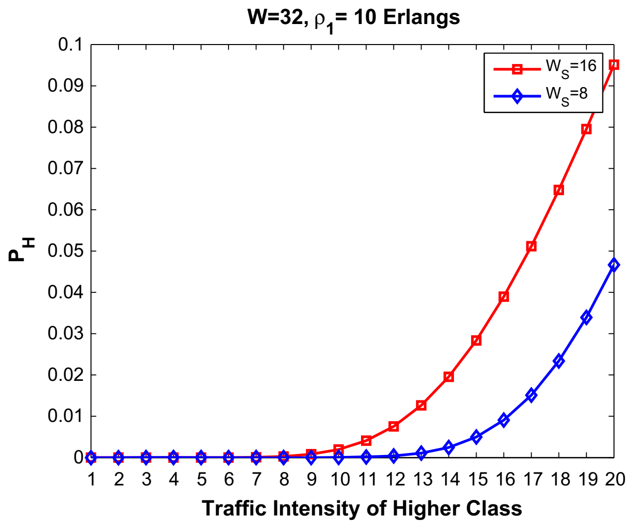

Figure 22 BLP of class H traffic.

6. Conclusion

In this paper, we presented an analytical model for the wavelength reservation based QoS differentiation mechanism in OBS networks. The model is studied in depth for a single class system and then generalized to a k-class service system. Through simulation, we examined the impact of higher priority traffic classes on the performance of lower priority classes in terms of blocking probability. During simulation, a shared traffic system is also examined to exhibit the QoS differentiation among multiple traffic classes. Through the numerical results, it is concluded that service classes with more allocated wavelengths experience lesser BLP compared to classless systems, while those with lesser wavelengths suffer heavy burst losses.

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