A Mathematical Framework for the Performance Evaluation of an All-Optical Packet Switch with QoS Differentiation

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***Abstract*—In this paper we propose a mathematical framework for the performance evaluation of an all-optical packet switch, in terms of packet blocking probability. We provide the analytical models for several QoS differentiation schemes, including wavelength conversion, packet dropping, pre-emptive dropping, fiber delay lines, and wavelength reservation. We demonstrate the accuracy of the proposed models by comparing the analytical results with that of simulation; the results are found to be quite satisfactory.**

***Keywords*-optical packet switching; wavelength division multiplexing; packet blocking probability; markov chains; quality of service.**

I. Introduction

Wavelength Division Multiplexing (WDM) is the most promising solution for the efficient utilization of the enormous bandwidth of an optical fiber [2]. In WDM optical networks, the bandwidth of an optical fiber is partitioned into multiple data channels, in which different messages can be transmitted simultaneously. Nowadays, the WDM technology is deployed in point-to-point architectures, where electronic devices are used to switch optical signals. However, traditional electronic packet switches are not suitable for handling such high bandwidth due to limitations of electronic processing speeds and due to the significant cost of high speed Optical-Electronic-Optical (O-E-O) converters [3]. Optical Packet Switching (OPS) is a promising sub-wavelength switching approach, since it is capable of dynamically allocating network resources with fine granularity and excellent scalability. In OPS networks the packet payload remains in the optical domain during the entire packet transmission from the origin to the destination node [4]. Even though the packet payload is switched transparently without O-E-O conversion, the packet header requires electronic processing. A long term approach of the OPS is to process, buffer and forward the entire packet (both header and payload) in the optical domain.

A vital problem in OPS networks is the resolution of packet contention which occurs at a switching node whenever two or more packets are switched on the same output wavelength, at the same time. In electrical packet-switched networks, contention is resolved with the store-and-forward technique, where packets that lost the contention are stored in a memory module, in order to be sent out at a later time to an available output port. This is possible because of the availability of electronic Random-Access Memory (RAM). Since there is no equivalent all-optical RAM technology, optical packet switches need to implement different approaches for contention resolution.

In OPS networks, popular contention resolution schemes include the use of Fiber Delay Lines (FDLs) [5], [6], wavelength conversion [7], [8] and deflection routing [9]. FDLs provide constant delay to optical packets, to avoid packet blocking and loss, when all output ports are busy upon packet arrival. Even though employing FDLs makes the switch bulky and expensive, especially in cases where large amount of data needs to be buffered [10], packet contention finds a straightforward solution by incorporating FDLs readily. Wavelength converters are used in an OPS switch to resolve optical packet blocking by transmitting a contending optical packet on another wavelength of the same fiber. Deflection routing is another way to minimize packet losses by routing packets, which lose the contention, to nodes different than their preferred next hop nodes, with the prospect that they will eventually reach their destinations [11]. The latter solution is not preferred in delay-sensitive services, such as real-time or interactive applications, because it may cause packet misordering upon arrival at the destination node.

Apart from wavelength conversion which is the most promising solution for optical packet blocking, other resolution schemes such as wavelength reservation, packet dropping and pre-emptive drop policy, must be employed, in order to provide Quality of Service (QoS) differentiation. Wavelength reservation is an access restricted scheme, where a number of wavelengths are reserved to benefit high priority service-classes [12]. In packet dropping, packets belonging to low priority service-classes are dropped with a certain probability, before destined to an output port [13]. In the

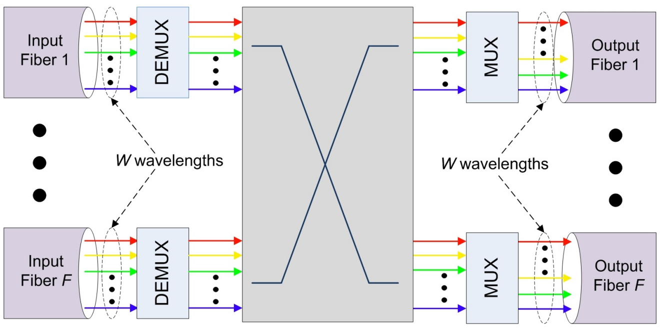

Figure 1. Generic configuration of an all-optical packet switch with F input/output fibers and W wavelengths per fiber.

pre-emptive drop policy, high priority packets pre-empt low priority packets (currently in transmission) in the case of contention.

The performance evaluation of an OPS switch, in terms of Packet Blocking (Loss) Probability (PBP), attracts notable research efforts [12]-[17]. We concentrate on Øverby's works [12]-[15], where analytical models for the PBP calculation in an all-optical packet switch, under the aforementioned QoS differentiation schemes, are presented. In [14], Øverby studied QoS differentiation schemes with wavelength converters for an asynchronous bufferless OPS switch, while the absence of wavelength converters was investigated in [15]. In all cases only two service-classes were considered (low and high priority) with infinite number of traffic sources. The utilization of FDLs in a slotted optical shared-buffer cross-connect is studied in [16], where a single service-class is considered. In [17] the authors present an analytical model for the calculation of the PBP in an all-optical packet switch equipped with tunable optical wavelength converters shared per output fiber that supports service-classes with different priorities.

In this paper, we extend our work presented in [1] and we propose analytical loss models for the PBP calculation in an all-optical packet switch that accommodates multiple service-classes of finite population, and supports QoS differentiation among them. The finite population assumption is essential, because the number of input ports in an all-optical packet switch is limited. Our study begins with the PBP determination in an all-optical packet switch with full wavelength conversion capability. The switch may operate without any QoS differentiation scheme, or adopt the intentional packet dropping policy, or the wavelength reservation policy (a number of wavelengths are reserved for each service-class). In addition, we study the all-optical packet switch which utilizes a number of FDLs in each output wavelength, by considering two cases: i) Packets belonging to a low priority service-class are intentionally forwarded to an FDL, before attempting to reach an output wavelength. In this way their arrival rate is reduced and therefore the probability that high-priority packets will occupy an output wavelength is increased. ii) Packets of a low priority service-class are not allowed to access the output wavelengths, when the number of occupied output wavelengths exceeds a predefined threshold. In that case, packets of the high-priority service-class are forwarded to an FDL.

Furthermore, we study the case of the absence of wavelength converters in the switch, where the QoS differentiation is employed either with the intentional packet dropping policy, or the pre-emptive drop policy. All the proposed models are computationally efficient since they are based on simple recurrent formulas. Our analysis is validated through simulation; the accuracy of the proposed models is found to be quite satisfactory.

The rest of the paper is organized as follows. In Section II, we present the analytical model for the PBP calculation in with full wavelength conversion capability in the case where i) no QoS differentiation scheme is applied (subsection II.A), ii) the intentional packet dropping policy is applied (subsection II.B), iii) the wavelength reservation policy is applied (subsection II.C), iv) the combination of the wavelength reservation policy and the intentional packet dropping policy is applied (sub-section II.D), and v) a number of FDLs is equipped in the switch (sub-section II.E). In Section III we present the analytical model for the PBP calculation in an all-optical switch without wavelength conversion capability i) under the intentional packet dropping policy (subsection III.A), and ii) under the pre-emptive drop policy (subsection III.B). Section IV is the evaluation section. Finally, we conclude is Section V.

II. All-Optical Packet Switch With Wavelegnth Conversion Capability

Fig. 1 shows the considered architecture of an all-optical packet switch with full wavelength conversion capability. The switch has F input and output fibers, while each input/output fiber supports W wavelengths. The bandwidth capacity of each wavelength is C bits/sec. Each one of the output fibers corresponds to a specific destination node. The OPS network accommodates K service-classes with different QoS priorities; service-class 1 has the lowest priority, while service-class K has the highest priority. Arriving packets at the switch are switched to the appropriate output fiber according to the packet header which is processed electronically. Since wavelength conversion is supported by the switch, a packet can be switched to any wavelength of the destination fiber, as long as at least one wavelength is available at the time instant the packet arrives at the switch. The arrival rate of service-class k packets ($k \in [1, K]$) is denoted as λ_k. We assume that the length of the packets is exponentially distributed with mean l_p, which is the same for all service-classes. The latter assumption is adopted in order to define the same service-time for each service-class; therefore, if a packet is accepted for service through an available wavelength, the time that this wavelength is occupied is $\mu^{-1} = l_p/C$, where μ is the service rate of the wavelength, (exponentially distributed). In the following subsections we present the analytical models for the PBP calculation both without any QoS differentiation scheme, and with QoS differentiation schemes: the intentional packet dropping policy, the wavelength reservation policy, and the utilization of FDLs. Although our analysis targets at the PBP calculation in one destination fiber, it can be applied to any output fiber of the all-optical packet switch.

A. Absence of QoS differentiation scheme

The absence of a QoS differentiation scheme means that all service-classes have the same priority; therefore, the PBP is the same for all service-classes. The calculation of the PBP is based on the knowledge of the occupancy distribution of the wavelengths in the fiber. To this end, we formulate a Markov chain with the state transition diagram of Fig. 2, where state *i*represents the number of occupied wavelengths in the fiber. We denote the total packet arrival rate from an input wavelength by$\lambda = \sum_{k=1}^{K} \lambda_k$.We also indicate the number of input wavelengths that offer traffic to the fiber under study, as $R_f, f \in [1, F]$, where $R_f = F \cdot W$, if we assume that all output fibers have the same traffic load. The transition from state [*i*-1] to state [*i*] of the Markov chain occurs [*Rf*-(*i*-1)]$\cdot\lambda$ times per unit time. This is because in state [*i*-1] the number of input wavelengths which have not been used for a connection establishment with an output port is $R_f - (i-1)$, while the call arrival rate is aggregated to λ, since a packet from any service-class is required for the occupation of the wavelength. The reverse transition, from state [*i*] to state [*i*-1] is realized *i* times per unit time, where μ is the service rate of a wavelength. The probability *P*(*i*) that *i* wavelengths are occupied in the fiber can be derived from the rate balance equations of the state transition diagram of Fig. 2. We use the classical method for deriving the distribution *P*(*i*) which is described in [18]. More specifically, from the global balance equations (rate-out = rate-in), we obtain the following steady-state equation:

$$\begin{aligned} &P(i-1)[(R_f-(i-1))\lambda] + P(i+1)[(i+1)\mu] = \\ &= P(i)[(R_f-i)\lambda + i\mu] \end{aligned} \quad (1)$$

where $P(i) = 0$ for $i < 0$ and $i > W$. By writing (1) for $i = 0$ to $i - 1$, and summing up side by side, we get the following recurrent formula:

$$P(i) = \frac{\lambda}{\mu}\frac{R_f-(i-1)}{i}P(i-1) \quad (2)$$

Consecutive applications of (2) yields the equation that gives the probability *P*(*i*) that *i* wavelengths (*i*=0,1,…,*W)* are occupied in the output fiber:

$$P(i) = \left(\frac{\lambda}{\mu}\right)^i \cdot \frac{\prod_{j=1}^{i}[R_f-(j-1)]}{i!} \cdot P(0) \quad (3)$$

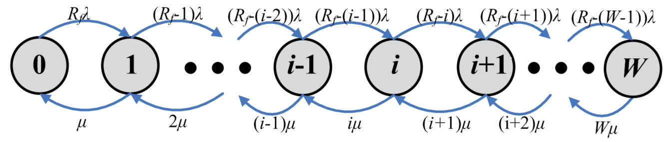

Figure 2. State transition diagram of the number of occupied wavelenths in the output fiber f, for the case of no QoS differentiation scheme.

The probability *P*(0) that the fiber is empty can be derived using the normalization condition,

$$\sum_{i=0}^{W} P(i) = 1 \quad (4)$$

Therefore, the probability *P*(0) is given by the following formula:

$$P(0) = \left[\sum_{n=0}^{W}\left(\frac{\lambda}{\mu}\right)^n \frac{\prod_{j=1}^{n}[R_f-(j-1)]}{n!}\right]^{-1} \quad (5)$$

It should be noted that the distribution of (3) is the well-known Engset distribution. The PBP is determined by (3) when *i*=*W*, i.e. *P*(*W*), since an input packet cannot be serviced when all the wavelengths are occupied. As a result, in the absence of any QoS differentiation scheme, the PBP is the same for all service-classes.

B. The intentional packet dropping policy

In the intentional packet dropping policy, a service-class *k* packet is dropped with a constant probability p_k, before reaching the output fiber. Since the first service-class has the lowest priority and the *K*-th service-class has the highest priority, $p_1 > p_2 > ... > p_K = 0$ i.e. a *K*-th service-class packet cannot be dropped. In order to favor specific service-classes, the values of the dropping probabilities p_k should be selected appropriately. In this case, the occupancy distribution of the wavelengths in the fiber could be derived from the state transition diagram of Fig. 2, with the substitution:

$$\lambda = \sum_{k=1}^{K} \lambda_k(1-p_k) \quad (6)$$

Following the same concept as in the case of no QoS differentiation scheme, the distribution of the occupied wavelengths in the output fiber is given by (3) and (5), where λ is given by (6). The PBP of a service-class *k* packet is given by:

$$B_k = p_k + (1-p_k)P(W) \quad (7)$$

since a service-class *k* packet can be blocked when the system is at any state with probability p_k, or at the last state (when all wavelengths are occupied) with probability $(1-p_k)P(W)$. Especially for the *K*-th service-class, the PBP is determined by $P(W)$, given that the K-th service-class has the highest priority and $p_k = 0$.

C. The Wavelength Reservation Policy

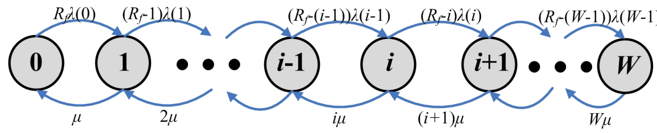

Figure 3. State transition diagram of the number of occupied wavelenths in the output fiber f, for the case of QoS differentiation scheme.

In the wavelength reservation policy a number of wavelengths in the output fiber is reserved exclusively for each service-class. More precisely, a service-class k packet is accepted for service, when more than tk wavelengths are available in the fiber. In order to reduce the PBP of the high priority service-classes, we assume that $t_1 > t_2 > ... > t_K$.The occupancy distribution of the fiber is described by the Markov chain of Fig. 3, where the arrival rate $\lambda(i)$ is given by:

$$\lambda(i) = \sum_{k=1}^{K} \lambda_k D_k(i) \tag{8}$$

where $D_k(i)$ is a parameter that equals to 1, if the number of the free wavelengths is less than or equal to t_k, or equals to 0, if the number of the free wavelengths is more than t_k; therefore, from the state transition diagram of Fig. 3 we derive the recursive formula:

$$P(i) = \frac{(R_f - (i-1))}{\mu \cdot i} \sum_{k=1}^{K} \lambda_k D_k(i-1) \cdot P(i-1) \tag{9}$$

where:

$$D_k(i-1) = \begin{cases} 1, \text{ for } i \leq W - t_k \\ 0, \text{ for } i > W - t_k \end{cases} \tag{10}$$

Eq. (9) can be solved by setting $P(0)$=1, ($P(i)$=0, i<0), and normalizing each value over the summation $\sum_{i=0}^{W} P(i)$. The PBP calculation of service-class k is based on the summation of the probabilities of the blocking states [W-t_k] to [W], and is given by the formula:

$$B_k = \sum_{j=W-t_k}^{W} P(j) \tag{11}$$

D. A combination of the intentional packet dropping and the wavelength reservation policies

Under the intentional packet dropping policy, a low priority packet is dropped with a constant probability, even when the number of the occupied wavelengths is low (at the time instant of the dropping). An alternative solution could be the activation of the intentional packet dropping policy, only when the number of occupied wavelengths in the fiber exceeds a pre-defined threshold. In this way we favor the high priority service-classes only when the number of the available output wavelengths is low. Since the first service-class has the lowest priority and the K-th service-class has the highest priority, the dropping probabilities for the K service-classes are defined as $p_1 > p_2 > ... > p_K = 0$, while the thresholds for the activation of the dropping policy are defined as $t_1 > t_2 > ... > t_K = 0$; therefore packets of the highest priority cannot be dropped. In this case, the occupancy distribution of the fiber is described by the Markov chain of Fig. 3, where the arrival rate of packets is given by (6) only when the number of the occupied wavelengths exceeds the threshold W-t_k for the specific service-class, while, the arrival rate of service-class k packets equals to λ_k, only when the number of the occupied wavelengths in the fiber is less than W-t_k, therefore:

$$\lambda(i) = \begin{cases} \sum_{k=1}^{K} \lambda_k(1-p_k), & \text{if } i \geq W - t_k \\ \sum_{k=1}^{K} \lambda_k, & \text{if } i < W - t_k \end{cases} \tag{12}$$

Following the same concept as in the case of no QoS differentiation scheme and based on the state transition diagram of Fig. 3 we derive the recursive formula:

$$P(i) = \frac{(R_f - (i-1))}{\mu \cdot i} \lambda(i-1) \cdot P(i-1) \tag{13}$$

Eq. (13) can be solved by setting $P(0)$=1, ($P(i)$=0, i<0), and normalizing each value over the summation $\sum_{i=0}^{W} P(i)$. The PBP calculation is based on the fact that a service-class k packet can be blocked at any one of the states from [W-t_k] to [W] with probability p_k, or at the last state (when all wavelengths are occupied) with probability (1-p_k)$P(W)$:

$$B_k = \sum_{j=W-t_k}^{W} p_k P(j) + (1-p_k) P(W) \tag{14}$$

It should be noted that if t_2=W, then the set of equations (12)-(14) calculates the PBP in an all-optical switch, which supports 2 service-classes, under the intentional packet dropping policy (sub-section II-B), using the same values for the dropping probabilities p_k. Furthermore, if $p_2 = 1$, the same set of equations calculates the PBP in an all-optical switch, which supports 2 service-classes, under the wavelength reservation policy (sub-section II-C), using the same values for the parameters t_k.

E. Utilization of FDLs

Optical buffering using FDLs could be used in several ways in order to provide QoS differentiation. We consider two cases in which the OPS network supports 2 service-classes with different priorities. In the first case, only low priority packets are forwarded to FDLs before attempting to reach an output wavelength. In the second case, when the number of occupied wavelengths exceeds a pre-defined threshold, packets that belong to the high priority service-class are forwarded to an FDL module before attempting to reach an output wavelength. In the following sub-sections we provide the analysis for the PBP calculation in both cases.

1) Delaying low priority packets through FDLs: We consider the case where low priority packets are forwarded to FDLs before attempting to reach an output wavelength. In this way the arrival rate λ_1 of the low priority packets is reduced and the high priority packets have increased probability to reserve an output wavelength. We assume that each wavelength is equipped with a module that contains an equal number of *L* FDLs. The length of each FDL is denoted by l_{FDL}; thus, the delay that a packet suffers during its transmission through an FDL is equal to the transmission delay plus the propagation delay of a packet:

$$h = \frac{l_p}{C} + \frac{l_{FDL}}{\tilde{c}} = \frac{l_p}{C} + \frac{l_{FDL} \cdot \tilde{n}}{c_o} \tag{15}$$

where $\tilde{c} = c_o/\tilde{n}$ is the speed of light in the optical fiber, *co* is the speed of light in the vacuum ($3 \cdot 10^8$m/sec) and $\tilde{n}$ is the refractive index of the optical fiber. Since the mean length packet l_p is exponentially distributed and $l_{FDL} \cdot \tilde{n}/_{c_o}$ is constant, *h* is also exponentially distributed.

The procedure of the postponement of the low priority packets through an FDL can be modeled as a loss system with a finite number of input traffic sources and *L* FDLs as the number of servers, as shown in Fig. 4. The number of the input traffic sources for each set of FDLs is not constant; it is a function of the number *i* of occupied wavelengths and consequently, the number of the input traffic sources to the FDL module of a wavelength is (R_f -*i*). Moreover, the arrival rate of each input traffic source is λ_1, since, only packets from the first service-class enter FDLs and the service time of FDLs is equal to *h*. This system can be described analytically by the Engset distribution:

$$q_i\left(j\right) = \left(\lambda_1 \cdot h\right)^j \cdot \frac{\prod_{m=1}^{j} \left[\left(R_f - i\right) - \left(m - 1\right)\right]}{j!} \cdot q_i\left(0\right) \tag{16}$$

The probability $q_i(0)$ that FDLs are empty, when *i* wavelengths are occupied in the output fiber, can be derived using the normalization condition, $\sum_{m=0}^{L} q_i\left(m\right) = 1$. The probability that a low priority packet will find all *L* FDLs occupied is given by $q_i(L)$; in this case the low priority packet is blocked and lost.

Since the number of the input ports to an FDL module is a function of the occupied wavelengths, it is possible that in case of high wavelength occupancy, the low priority packets can not be blocked because of the unavailability of an FDL; they are only delayed by their transmission through an FDL. This situation occurs when the number of the input traffic sources is less than the numbers of FDLs in the FDL module. Therefore, the rate by which the packets egress the FDLs and request access to the wavelength is $L \cdot 1/h$, when the number of input ports is larger than *L*; if this number is less than *L*, no packets are blocked in the FDLs and the egress rate of the packets is $(R_f - i) \cdot 1/h$. This rate is added to the rate of the high priority packets, which is $(R_f - i) \cdot \lambda_2$. In the case of $(R_f - i) < L$, in order to achieve the reduction of the arrival rate of the low priority packets, this delay has to be larger than the inter-arrival time of the packets. The total arrival rate of packets, when *i* output wavelengths are occupied in the output fiber, is given by:

$$\lambda(i) = \begin{cases} (R_f - i) \cdot \lambda_2 + L \cdot \frac{1}{h} & \text{if } L < (R_f - i) \\ (R_f - i) \cdot \left(\lambda_2 + \frac{1}{h}\right) & \text{if } L \geq (R_f - i) \end{cases} \tag{17}$$

In order to calculate the distribution of the occupied wavelengths in the output fiber we construct the Markov chain of Fig. 5. By following the same procedure as in the case of no QoS differentiation scheme and based on the state transition diagram of Fig. 5, we derive the recursive formula:

$$P\left(i\right) = \frac{\lambda\left(i-1\right)}{i \cdot \mu} \cdot P\left(i-1\right) \tag{18}$$

Eq. (18) can be solved by setting *P*(0)=1, (*P*(*i*)=0, *i*<0), and normalizing each value over the summation $\sum_{i=0}^{W} P(i)$. The PBP of low and high priority service-classes are respectively given by:

$$\begin{aligned} B_1 &= \textstyle\sum_{i=0}^{W-1} P(i) \cdot q_i(L) + P(W) \\ B_2 &= P(W) \end{aligned} \tag{19}$$

since a low priority packet can be blocked when the system is at any state with probability $q_i(L)$ (blocked in the FDL module), or at the last state (when all wavelengths are occupied) with probability *P*(*W*).

2) Combining the wavelength reservation policy with the utilization of FDLs: We consider the case where the number of wavelengths is divided into two groups. The first group consists of $W - W_T$ wavelengths which are available for servicing packets of both service-classes. If the number of the occupied wavelengths in the output fiber exceeds the threshold $W - W_T$, then only packets of the high priority service-class are forward to an FDL module. Each one of the remaining W_T wavelengths (of the second group of wavelengths) is equipped with *L* FDLs. Packets that egresses the FDLs are able to attempt reaching one of the W_T wavelengths. Following the assumptions for the FDLs, presented in the previous sub-section, we define the arrival rate of the packets, when *i* output wavelengths are occupied as:

$$\lambda(i) = \begin{cases} (R_f - i) \cdot (\lambda_1 + \lambda_2) \ \ \text{if } i \leq W - W_T \\ L \cdot \frac{1}{h} \text{ if } i > W - W_T \text{ and } L < (R_f - i) \\ (R_f - i) \cdot \frac{1}{h} \text{ if } i > W - W_T \text{and} L \geq (R_f - i) \end{cases} \tag{20}$$

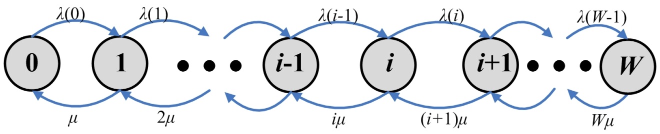

Figure 4. State transition diagram of the number of occupied wavelenths in the output fiber f, for the case where the all-optical switch utilizes an FDL module.

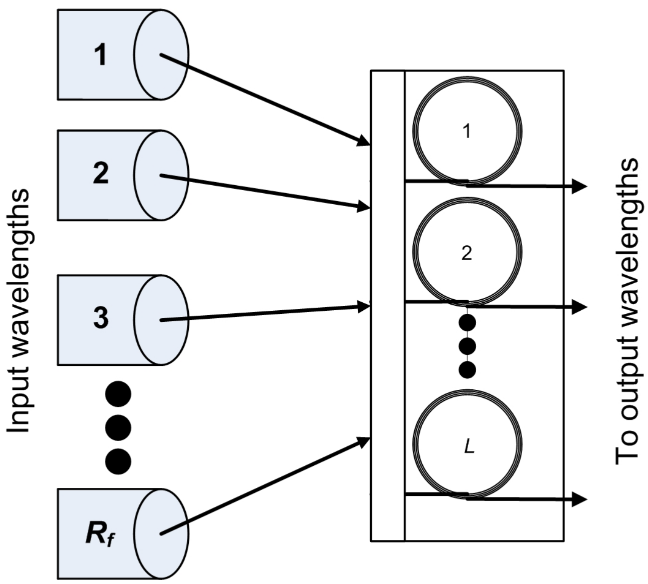

Figure 5. Schematic diagram of the module of L FDLs and R_f input wavelengths.

The distribution of the occupied wavelengths in the output fiber is given by (18) where the arrival rate $\lambda(i)$ is given by (20). The PBP of the low priority service-class is given by the summation of the probabilities of the blocking states $[W - W_T + 1]$ to [W]:

$$B_1 = \sum_{i=W-W_T+1}^{W} P(i) \tag{21}$$

The PBP calculation of the high priority service-class is based on the fact that a packet can be blocked in the FDL module at any one of the states from [W-t_k+1] to [W-1] with probability $q_i(L)$ (given by (16)) or at the last state (when all wavelengths are occupied) with probability $P(W)$:

$$B_2 = \sum_{i=W-W_T+1}^{W-1} q_i(L) \cdot P(i) + P(W) \tag{22}$$

III. All-Optical Packet Switch Without Wavelength Conversion Capability

The analysis of an all-optical switch without wavelength conversion capability could be considered as a special case of the analysis of an all-optical switch with wavelength conversion capability, presented in Section II. More precisely, we focus on the determination of the occupancy distribution of one output wavelength; therefore this analysis could be used to any output wavelength of any output fiber. In the following subsections we present the analytical models for the PBP calculation in an all-optical packet switch that operates under the intentional packet dropping policy, or the pre-emptive drop policy.

A. The Intentional Packet Dropping Policy

We assume that the switch operates under the intentional packet dropping policy; therefore a service-class k packet is dropped with a constant probability p_k, before reaching the output fiber. Since an output wavelength can be idle (state 0) or busy (state 1), we formulate a Markov chain with the state transition diagram of Fig. 6, where the total arrival rate is given by (6) and $R_{f,w}$ denotes the number of input wavelengths that offer traffic to the wavelength under study. By solving the Markov chain of Fig. 6, we derive the steady-state probabilities:

$$\begin{aligned} P(0) &= \tfrac{\mu}{R_{f,w}\lambda+\mu} \\ P(1) &= \tfrac{R_{f,w}\lambda}{R_{f,w}\lambda+\mu} \end{aligned} \tag{23}$$

Following the same analysis as in the full wavelength conversion case, the PBP of service-class k packets is given by:

$$B_k = p_k + (1 - p_k) \cdot P(1) \tag{24}$$

B. The Pre-Emptive Drop Policy

In the pre-emptive drop policy, high priority packets pre-empt low priority packets currently in transmission in the case of contention. In our study, we assume that the all-optical network supports 3 service-classes. When the wavelength under study is occupied, packets that belong to service-class 1 will be blocked, while packets that belong to the other two service-classes are permitted to interrupt the transmission of a service-class 1 packet, and pre-empt the wavelength. We assume that the successful pre-emption of a service-class 1 packet by a packet that belongs to service-class 2 and 3 is realized with probability p_2 and p_3, respectively. We define that service-class 3 packets have higher priority than service-class 2 packets, therefore $p_2 < p_3$. By fine-tuning the values of p_2 and p_3 we can adjust the PBP of service-class 2 and 3, respectively, to any desired level.

In order to model the all-optical switch without wavelength conversion capability, under the pre-emptive drop policy, we construct the Markov chain of Fig. 7. State [0, 0] is the idle state, while states [1, 1], [1, 2] and [1, 3] indicate the states where the wavelength is occupied by a service-class 1, 2 or 3 packet, respectively. When the system is idle, it is transferred to state [1, m], m=1, 2, 3, $R_{f,w} \cdot \lambda_m$ times per

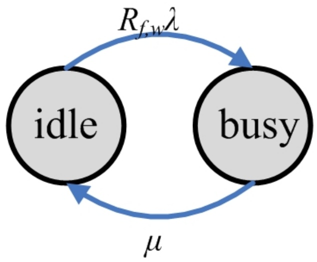

Figure 6. State transition diagram of the number of occupied wavelenths in the output fiber of the switch without wavelength conversion, under the intentional packet dropping policy.

unit time, where $R_{f,w}$ is the number of input wavelengths that offer traffic to the wavelength under study. When the system is at state [1, 1], it can be transferred to state [1, 2] $R_{f,w} \cdot \lambda_2 \cdot p_2$ times per unit time. This transition refers to the case where a service-class 1 packet is pre-empted by a service-class 2 packet. Similarly, when the system is at state [1, 1], it can be transferred to state [1, 3] $R_{f,w} \cdot \lambda_3 \cdot p_3$ times per unit time, when a service-class 3 packet pre-empts a service-class 1 packet. Solving the Markov chain of Fig. 7, we obtain the following state probabilities:

$$\begin{aligned}
P(0,0) &= \frac{\mu}{R_{f,w}(\lambda_1+\lambda_2+\lambda_3)+\mu} \\
P(1,1) &= \frac{\lambda_3 R_{f,w}\mu}{(R_{f,w}(\lambda_1+\lambda_2+\lambda_3)+\mu)(\lambda_3 R_{f,w}p_3+\lambda_2 R_{f,w}p_2+\mu)} \\
P(1,2) &= \frac{\lambda_2 R_{f,w}(\lambda_3 R_{f,w}p_3+p_2 R_{f,w}(\lambda_3+\lambda_2)+\mu)}{(R_{f,w}(\lambda_1+\lambda_2+\lambda_3)+\mu)(\lambda_3 R_{f,w}p_3+\lambda_2 R_{f,w}p_2+\mu)} \\
P(1,3) &= \frac{\lambda_3 R_{f,w}((\lambda_3+\lambda_1)R_{f,w}p_3+\lambda_2 R_{f,w}p_2+\mu)}{(R_{f,w}(\lambda_1+\lambda_2+\lambda_3)+\mu)(\lambda_3 R_{f,w}p_3+\lambda_2 R_{f,w}p_2+\mu)}
\end{aligned} \tag{25}$$

A service-class 3 packet is blocked when the system is at state [1, 3] or either at state [1, 2], or at state [1, 1] and pre-emption fails. Similarly, a service-class 2 packet is blocked when the system is at state [1, 2] or either at state [1, 3], or state [1, 1] and pre-emption fails. A service-class 1 packet is blocked when the system is at states [1, 2] or [1, 3] or [1, 1] and pre-emption by a service-class 2 or 3 packet successfully occurs. Therefore the PBP of the three service-classes (B_1, B_2 and B_3, respectively) can be calculated using the formulas:

$$\begin{aligned}
B_1 &= P(1,3)+P(1,2)+P(1,1)\left(1+\frac{p_3\lambda_3}{\lambda_1}+\frac{p_2\lambda_2}{\lambda_1}\right) \\
B_2 &= P(1,3)+P(1,2)+(1-p_2)P(1,1) \\
B_3 &= P(1,3)+P(1,2)+(1-p_3)P(1,1)
\end{aligned} \tag{26}$$

IV. Evaluation

In this section, we evaluate the proposed analytical models through simulation. To this end, we simulate the different functions of the all- presented in section II and III, by using the Simscript II.5 simulation tool [19]. We examine the blocking performance of the all-optical packet switch, with or without wavelength conversion, by providing two application examples.

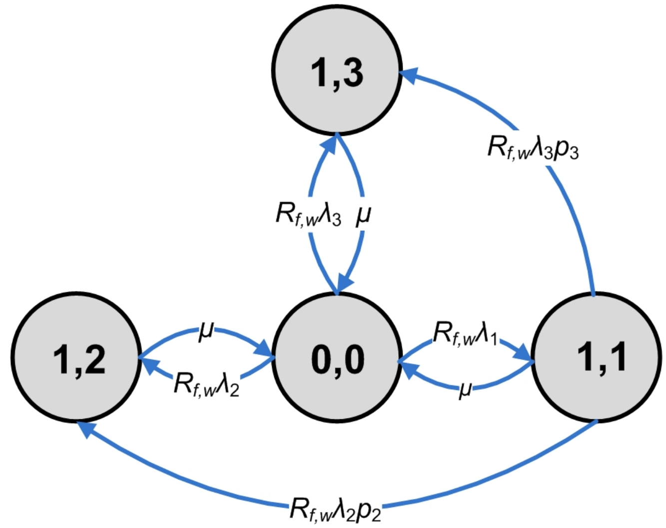

Figure 7. State transition diagram of the number of occupied wavelenths in the output fiber of the switch without wavelength conversion, under the pre-emptive drop policy.

In the first example we consider an all-optical packet switch with wavelength conversion capability. The number of the input/output fibers are F=10, while each fiber supports W=8 wavelengths. The capacity of each wavelength is C= 10 Gbit/sec. Packets that belong to K=2 service-classes arrive at the switch and they are switched to the appropriate output fiber. We calculate the PBP in one output fiber, while considering that an equal traffic load is offered to every output fiber, i.e. $R_f = F \cdot W$. The length of the packets that belong to all service-classes is exponentially distributed with mean value of 15 Kbytes. In Table I we present analytical and simulation PBP results for the case of no QoS differentiation policy versus the arrival rate per idle input wavelength. Since no QoS differentiation scheme is considered, the PBP is the same for the two service-classes. The comparison between analytical and simulation results reveals that the accuracy of the proposed analytical model is completely satisfactory.

The effect of the application of the intentional packet

Table I
Analysis Versus Simulation For The PBP In The Case Of No QoS Differentiation Scheme

Arrival rate (packets/sec)		Packet Blocking Probability (PBP)		
1^{st} serv.	2^{nd} serv.	Analysis(%)	Simulation	
			Mean (%)	95% Conf. Interval
500	1000	0.00766	0.00756	6.2×10^{-5}
750	1250	0.04858	0.04820	7.5×10^{-4}
1000	1500	0.17883	0.17742	2.6×10^{-3}
1250	1750	0.48379	0.47999	5.6×10^{-3}
1500	2000	1.04937	1.04114	9.1×10^{-3}
1750	2250	1.94094	1.92571	2.8×10^{-2}
2000	2500	3.18720	3.16220	4.3×10^{-2}

dropping policy to the PBP is shown in Table II. A packet that belongs to the first service-class is dropped with a constant probability p_1=0.05, while packets that belong to the second service-class cannot be dropped. As Table II shows, the model's accuracy is satisfactory. We notice that the PBP of the second service-class is reduced, compared to the corresponding results of Table I, while the PBP of the first service-class is increased. This is due to the fact that 5% of the first service-class packets are dropped, before reaching an output wavelength; therefore packets that belong to the second service-class have privileged access to the output wavelengths. Moreover, in Figs. 8 and 9 we present analytical PBP results for both service-classes, respectively, versus the packet arrival rate, for various values of the dropping probability p_1. We consider 7 arrival-rate points (1, 2, …, 7) in the x-axis of Figs. 8 and 9. Point 1 corresponds to$\lambda = (500,\ 1000)$packets/sec, and in the successive points the values of λ_1, λ_2 are equally increased by 250 packets/sec. The last Point 7 corresponds to (2000, 2500). Comparison of the results of Figs. 8 and 9 clearly reveals that the PBP of the first service-class strongly increases with the increase of the dropping probability p_1, while the PBP of the second service-class is softly affected by this increase.

The effect of the wavelength reservation policy on the PBP is presented in Table III. We assume the same scenario for the all-optical switch as in the two previous cases, while t_1=1 out of W=8 wavelengths are reserved for the packets of the second service-class (note that t_2=0). As the results reveal, the accuracy of the presented analytical model is quite satisfactory.

The impact of the increase of the wavelength threshold t_1 to the PBP of both service-classes can be monitored in Figs. 10 and 11. In particular, Figs. 10 and 11 illustrate the PBP of both service-classes against the arrival rate, for different values of the threshold t_1. We employ the same arrival-rate points, as the ones used in Figs. 8 and 9. The study of these figures reveals that the increase of t_1 results to the PBP decrease of the second service-class; the reverse performance is observed for the PBP of the first service-class. The explanation for this behavior is as follows: for high values of t_1 more wavelengths are reserved for

Table II
ANALYSIS VERSUS SIMULATION FOR THE PBP IN THE CASE OF THE INTENTIONAL PACKET DROPPING POLICY

Arrival rate		PBP 1^{st} service-class		PBP 2^{nd} service-class	
1^{st}	2^{nd}	Analysis(%)	Simulation	Analysis(%)	Simulation
500	1000	5.0058	$4.964 \pm 6.9 \times 10^{-2}$	0.006	$0.006 \pm 3.4 \times 10^{-5}$
750	1250	5.0374	$4.995 \pm 6.6 \times 10^{-2}$	0.039	$0.039 \pm 1.7 \times 10^{-4}$
1000	1500	5.1428	$5.099 \pm 7.1 \times 10^{-2}$	0.151	$0.149 \pm 2.3 \times 10^{-3}$
1250	1750	5.3932	$5.348 \pm 4.2 \times 10^{-2}$	0.414	$0.411 \pm 6.2 \times 10^{-3}$
1500	2000	5.8662	$5.817 \pm 1.5 \times 10^{-2}$	0.912	$0.904 \pm 2.1 \times 10^{-2}$
1750	2250	6.6243	$6.569 \pm 4.5 \times 10^{-2}$	1.709	$1.696 \pm 2.9 \times 10^{-2}$
2000	2500	7.7002	$7.636 \pm 6.0 \times 10^{-2}$	2.842	$2.819 \pm 6.0 \times 10^{-2}$

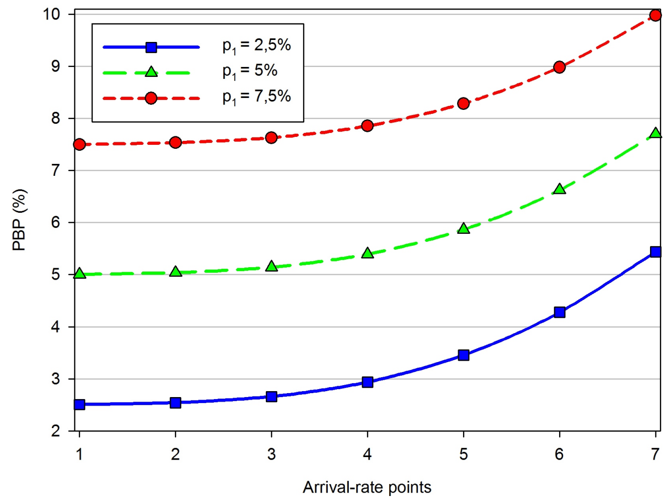

Figure 8. Analytical PBP results versus the arrival rate for different values of the dropping probability p1, for the first service-class of the first example, under the intentional dropping policy.

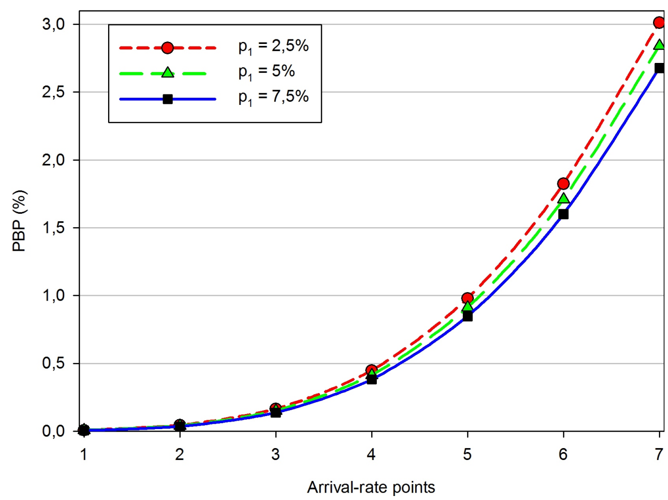

Figure 9. Analytical PBP results versus the arrival rate for different values of the dropping probability p_1, for the second service-class of the first example, under the intentional dropping policy.

the second service-class, thus packets that belong to this service-class have increased probability to access the output wavelengths of the output fiber, compared to packets that belong to the first service-class.

The evaluation of the combination of the intentional packet dropping policy and the wavelength reservation policy is realized through the comparison of analytical and simulation PBP results versus the packet arrival rate, as presented in Table IV. The results were obtained under the first application example, while the dropping probability of the first service-class is p_1= 0.05 and t_1 = 1 out of 8 wavelengths are reserved for the second service-class. As the results of the Table IV reveal, the accuracy of the proposed analytical model is quite satisfactory. Since the results of

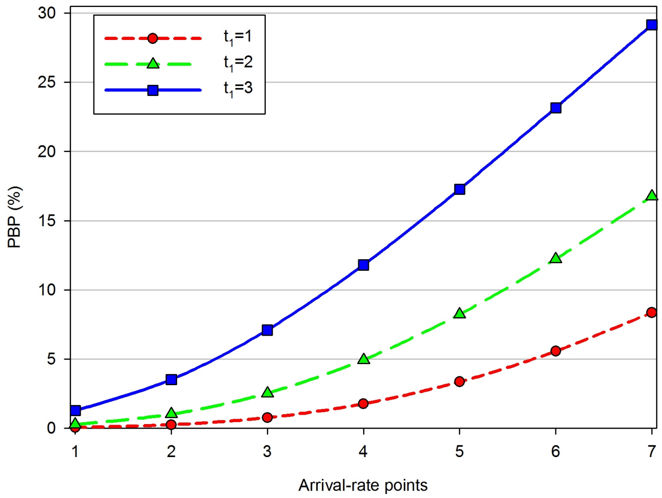

Figure 10. Analytical PBP results versus the arrival rate for different values of the threshold t_1, for the first service-class of the first example, under the intentional packet dropping policy.

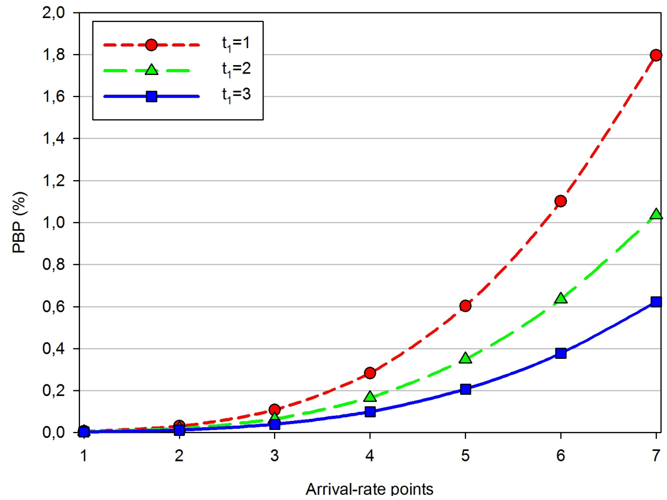

Figure 11. Analytical PBP results versus the arrival rate for different values of the threshold t_1, for the second service-class of the first example, under the intentional packet dropping policy.

Table IV were obtained by considering that only t_1=1 out of 8 wavelengths are reserved for the second service-class, there is a small benefit for packets of this service-class, over packets of the first service-class. The effect of the number of wavelengths that are reserved for the high priority service-class is depicted in Figs. 12 and 13. More precisely, Figs. 12 and 13 show the PBP of the two service-classes, respectively, versus the arrival rate, for different values of the threshold t_1, while the dropping probability p_1 is kept constant and equal to 0.05. As the results of Figs. 12 and 13 reveal, the increase of the value of t_1 has a small influence on the PBP performance of the high priority second service-class. On the other hand, increasing t_1 results in higher PBP values for the low priority service-class. Therefore, in order to benefit the high priority service-class, both the dropping probabilities p_k and the thresholds t_k should be carefully adjusted.

The first application example is also employed in order to evaluate the analytical models for the PBP calculation in an all-optical switch that utilizes FDLs. In the case where low priority packets are delayed by their transmission through a number of FDLs, we consider that each wavelength in the output fiber is equipped with a module that contains an equal number of $L = 4$ FDLs. The length of each FDL is denoted by $l_{FDL} = 5$ km, while the refractive index of the fiber that is used for the construction of the FDLs is n=1.55. In Table V we present analytical and simulation PBP results for the two service-classes against the arrival rate. The comparison of analytical and simulation results reveals that the accuracy of the proposed analytical model is satisfactory.

We also study the effect of the number of the FDLs in each FDL module, to the PBP of both service-classes. Fig. 14 presents analytical PBP results of both service-classes, versus the number of FDLs. We assume that the length of each FDL is $l_{FDL} = 5$ km, while the packet arrival rate of both service-classes is (λ_1, λ_2)=(300,500) packets/sec. Fig. 14 shows that when more FDLs are used in the FDL module, the PBP of the low priority service-class decreases; the reverse behavior is observed for the high priority service-class. For higher number of FDLs the PBP of both service-classes becomes the same and increases with further increase of the number of FDLs. This is due to the fact that when

Table III
ANALYSIS VERSUS SIMULATION FOR THE PBP IN THE CASE OF THE WAVELENGTH RESERVATION POLICY

Arrival rate		PBP 1^{st} service-class		PBP 2^{nd} service-class	
1^{st}	2^{nd}	Analysis(%)	Simulation	Analysis(%)	Simulation
500	1000	0.0518	$0.0512 \pm 5.5 \times 10^{-4}$	0.0051	$0.0050 \pm 8.9 \times 10^{-5}$
750	1250	0.2485	$0.2459 \pm 2.1 \times 10^{-3}$	0.0299	$0.0295 \pm 1.1 \times 10^{-4}$
1000	1500	0.7611	$0.7534 \pm 5.4 \times 10^{-3}$	0.1074	$0.1058 \pm 4.4 \times 10^{-3}$
1250	1750	1.7585	$1.7407 \pm 2.1 \times 10^{-2}$	0.2828	$0.2787 \pm 8.2 \times 10^{-3}$
1500	2000	3.3528	$3.3189 \pm 3.5 \times 10^{-2}$	0.6023	$0.5937 \pm 1.9 \times 10^{-2}$
1750	2250	5.5705	$5.5142 \pm 5.9 \times 10^{-2}$	1.1011	$1.0854 \pm 6.7 \times 10^{-2}$
2000	2500	8.3572	$8.2728 \pm 9.0 \times 10^{-2}$	1.7961	$1.7704 \pm 8.4 \times 10^{-2}$

Table IV
ANALYSIS VERSUS SIMULATION FOR THE PBP IN THE CASE OF THE COMBINATION OF THE WAVELENGTH RESERVATION AND THE INTENTIONAL PACKET DROPPING POLICY

Arrival rate		PBP 1^{st} service-class		PBP 2^{nd} service-class	
1^{st}	2^{nd}	Analysis(%)	Simulation	Analysis(%)	Simulation
500	1000	0.0097	$0.0096 \pm 2.2 \times 10^{-4}$	0.0074	$0.0073 \pm 5.4 \times 10^{-3}$
750	1250	0.0573	$0.0565 \pm 5.8 \times 10^{-3}$	0.0464	$0.0459 \pm 3.5 \times 10^{-3}$
1000	1500	0.2061	$0.2032 \pm 8.9 \times 10^{-3}$	0.1735	$0.1717 \pm 6.8 \times 10^{-3}$
1250	1750	0.5434	$0.5356 \pm 1.8 \times 10^{-2}$	0.4697	$0.4650 \pm 2.5 \times 10^{-2}$
1500	2000	1.1566	$1.1401 \pm 3.0 \times 10^{-2}$	1.0197	$1.0094 \pm 4.0 \times 10^{-2}$
1750	2250	2.1091	$2.0789 \pm 4.1 \times 10^{-2}$	1.8874	$1.8683 \pm 5.8 \times 10^{-2}$
2000	2500	3.4251	$3.3761 \pm 8.0 \times 10^{-2}$	3.1014	$3.0701 \pm 6.8 \times 10^{-2}$

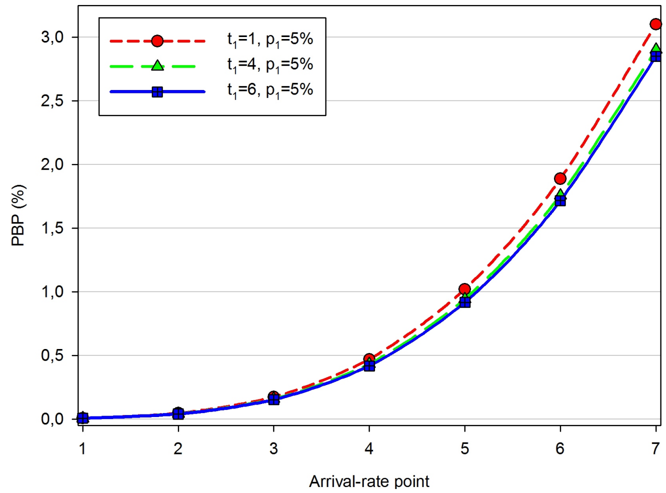

Figure 12. Analytical PBP results versus the arrival rate for different values of the threshold t_1, for the first service-class of the first example, under the wavelength reservation with intentional packet dropping policy.

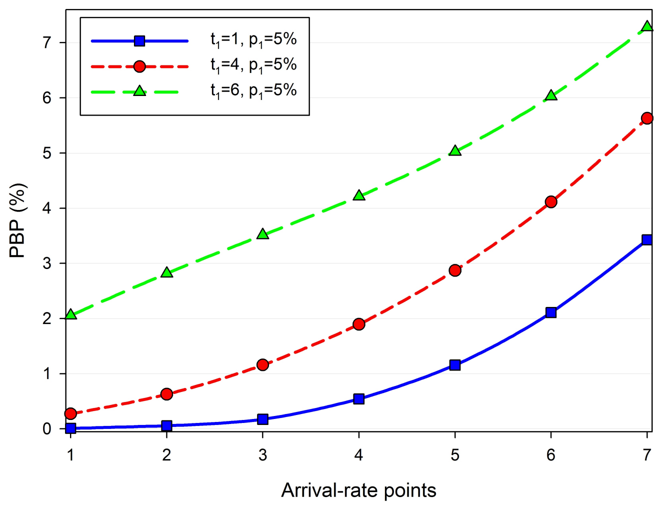

Figure 13. Analytical PBP results versus the arrival rate for different values of the threshold t_1, for the second service-class of the first example, under the wavelength reservation with intentional packet dropping policy.

few FDLs are employed, most of the low priority packets are blocked in the FDL module and high priority packets have increased probability to find an available output wavelength. By installing more FDLs in the FDL module, the difference between the PBP of both service-classes is reduced, while higher number of FDLs corresponds to higher input packet sources to the switch, which results in higher PBP for both service-classes.

Apart from the number of FDLs installed in each FDL module, another parameter that affects PBP is the length of each FDL. In Fig.15 we present analytical PBP results of both service-classes versus the length of an FDL. We assume that each FDL module consists of $L = 4$ FDLs, while the packet arrival rate of both service-classes is (λ_1, λ_2)=(300,500) packets/sec. Fig. 15 shows that the increase of the FDL length results in a PBP decrease of the high priority service-class, while the PBP of the low priority service-class has a decrease up to a certain value of the FDL length; after this point the PBP increases. The explanation for this behavior is as follows. When the FDL length is small, the delay that low priority packets experience is low and therefore the rate by which packets egress the FDL is high, compared to the rate when the FDL length is large. In the latter case, fewer low priority packets request service through an output wavelength; therefore high priority packets have privileged access to the output wavelengths.

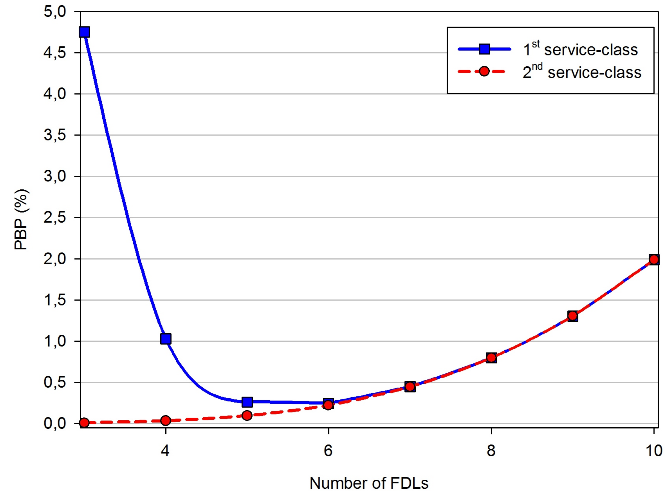

Figure 14. Analytical PBP results versus the number of FDLs for the two service-classes of the first example, for the case of delaying low priority packets through FDLs.

The analytical model for the combination of the wavelength reservation policy with the utilization of FDLs is evaluated by comparing analytical and simulation results, as they are presented in Table VI. In particular, in Table VI we present analytical and simulation PBP results, for different values of packet arrival rate, for both service-classes. We consider the first application example, while each wavelength in the output fiber is equipped with a module that contains an equal number of $L = 4$ FDLs. Also, the length of each FDL is denoted by $l_{FDL} = 5$

Table V
ANALYSIS VERSUS SIMULATION FOR THE PBP IN THE CASE OF DELAYING LOW PRIORITY PACKETS THROUGH FDLS

Arrival rate		PBP 1^{st} service-class		PBP 2^{nd} service-class	
1^{st}	2^{nd}	Analysis(%)	Simulation	Analysis(%)	Simulation
200	400	0.2887	$0.2845\pm3.2\times10^{-4}$	0.0245	$0.0241\pm2.4\times10^{-4}$
300	500	1.0291	$1.0144\pm2.1\times10^{-3}$	0.0344	$0.0339\pm2.5\times10^{-4}$
400	600	2.3961	$2.3619\pm3.3\times10^{-3}$	0.0474	$0.0467\pm3.2\times10^{-4}$
500	700	4.3752	$4.3127\pm5.8\times10^{-3}$	0.0639	$0.0630\pm5.5\times10^{-4}$
600	800	6.8585	$6.7605\pm9.1\times10^{-3}$	0.0847	$0.0835\pm7.6\times10^{-4}$
700	900	9.7035	$9.5648\pm4.2\times10^{-3}$	0.1103	$0.1087\pm1.3\times10^{-3}$
800	1000	12.771	$12.589\pm6.6\times10^{-2}$	0.1414	$0.1394\pm2.1\times10^{-3}$

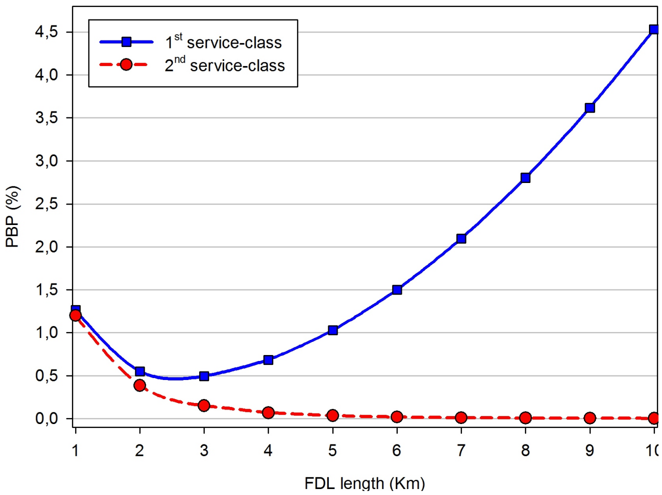

Figure 15. Analytical PBP results versus the length of each FDL for the two service-classes of the first example, for the case of delaying low priority packets through FDLs.

km and 2 out of 8 wavelengths are reserved for the high priority service-class. As the results reveal, the accuracy of the proposed analytical model is satisfactory. We also study the impact of the wavelength threshold W_T to the PBP. To this end, Fig. 16 and 17 presents analytical PBP results of both service-classes, respectively, versus the arrival rate, for different values of the parameter W_T. We consider 7 arrival-rate points (1, 2, …, 7) in the x-axis of Figs. 16 and 17. Point 1 corresponds to $(\lambda_1, \lambda_2) = (500, 1000)$ packets/sec, and in the successive points the values of λ_1, λ_2 are equally increased by 250 packets/sec. Thus, Point 7 corresponds to (2000, 2500). As it was anticipated, the increase of W_T results in the increase of the difference of PBP of the two service-classes, since more wavelengths are dedicated to exclusively service high priority packets.

In the second application example, we consider an all-optical switch without wavelength conversion capability. The number of the input fibers are again *F*=10, while each fiber supports *W*=8 wavelengths. The capacity of each wavelength is *C*= 10 Gbit/sec. Packets that belong to *K*=3 service-classes

Table VI
ANALYSIS VERSUS SIMULATION FOR THE PBP IN THE CASE OF THE COMBINATION OF THE WAVELENGTH RESERVATION AND THE UTIZATION OF FDLS

Arrival rate		PBP 1^{st} service-class		PBP 2^{nd} service-class	
1^{st}	2^{nd}	Analysis(%)	Simulation	Analysis(%)	Simulation
500	1000	0.0615	$0.0606 \pm 1.4 \times 10^{-4}$	0.0091	$0.0090 \pm 2.2 \times 10^{-4}$
750	1250	0.2879	$0.2838 \pm 5.5 \times 10^{-4}$	0.0557	$0.0552 \pm 7.7 \times 10^{-4}$
1000	1500	0.8611	$0.8488 \pm 4.9 \times 10^{-3}$	0.2148	$0.2126 \pm 1.3 \times 10^{-3}$
1250	1750	1.9447	$1.9169 \pm 7.3 \times 10^{-3}$	0.5937	$0.5877 \pm 2.8 \times 10^{-3}$
1500	2000	3.6289	$3.5770 \pm 3.1 \times 10^{-2}$	1.2946	$1.2815 \pm 6.9 \times 10^{-3}$
1750	2250	5.9101	$5.8256 \pm 4.5 \times 10^{-2}$	2.3779	$2.3538 \pm 2.8 \times 10^{-2}$
2000	2500	8.7080	$8.5835 \pm 6.6 \times 10^{-2}$	3.8501	$3.8112 \pm 8.2 \times 10^{-2}$

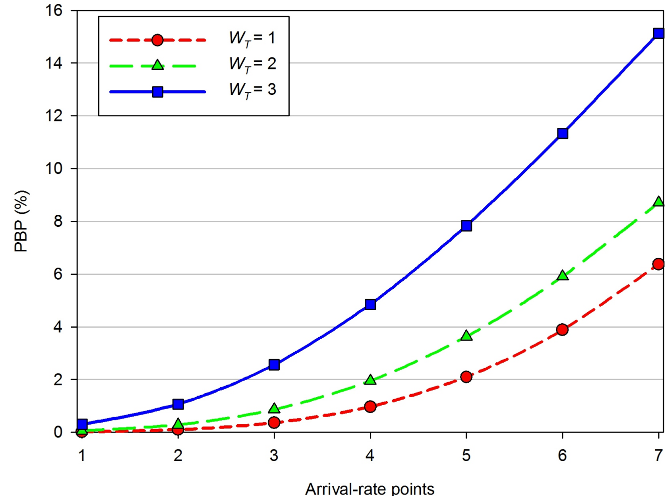

Figure 16. Analytical PBP results for the first service-class of the first example, under the combination of the wavelength reservation policy and the utilization of FDLs.

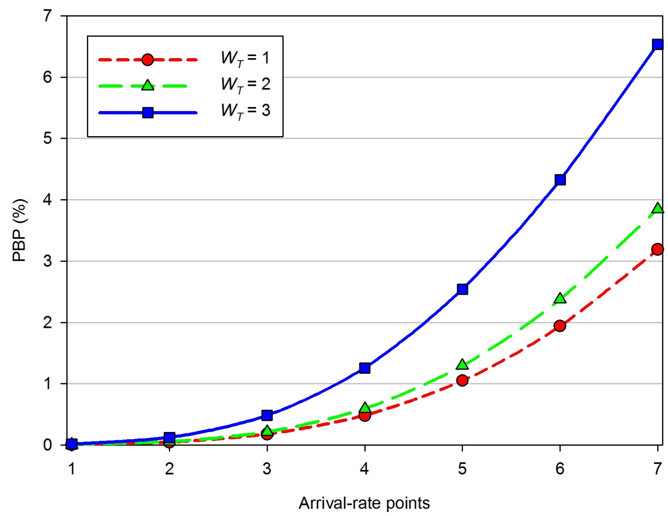

Figure 17. Analytical PBP results for the second service-class of the first example, under the combination of the wavelength reservation policy and the utilization of FDLs.

arrive at the switch and they are switched to the same output wavelength. We study the blocking performance of a single wavelength, considering that an equal traffic load is offered to every output fiber, i.e. $R_{f,w} = F \cdot W$. The dropping probability of the second and third service-classes is $p_2 = 0.01$ and $p_3 = 0.02$, respectively, while packets from the first service-class are not dropped. In Fig. 18 we present analytical PBP results of the three service-classes, where the arrival rate is the same for all service-classes. As the results reveal, packets of the second and third service-classes suffer higher blockings, compared to packets of the first service-class. The same scenario is used to study the pre-emption drop policy. The successful pre-emption of a service-class

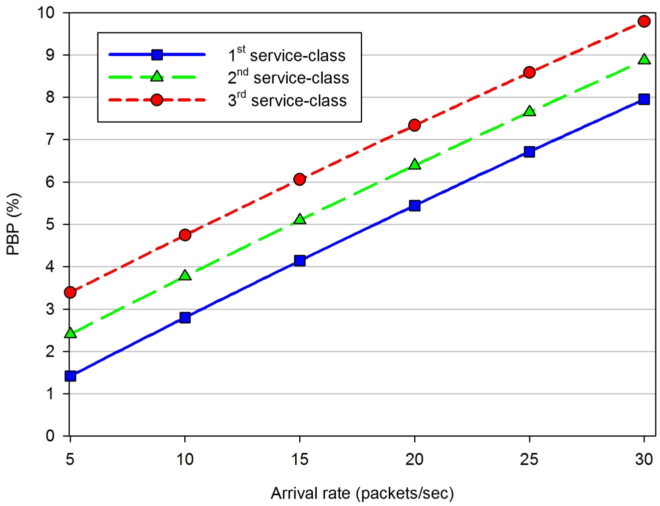

Figure 18. Analytical PBP results for the three service-classes of the second example, under the intentional packet dropping policy.

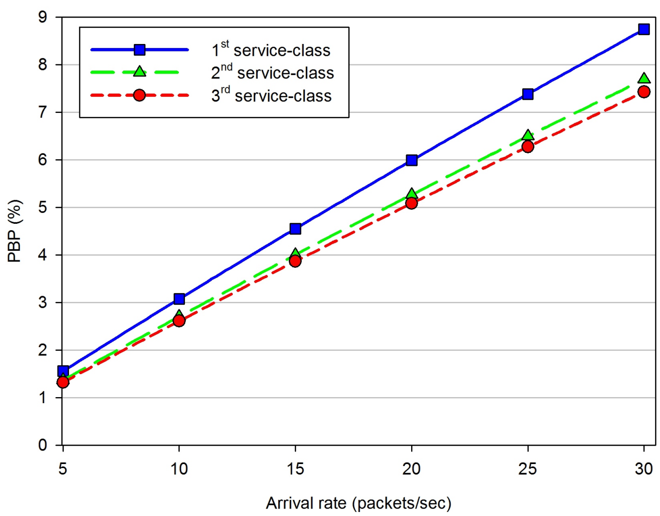

Figure 19. Analytical results PBP for the three service-classes of the second example, under the pre-emption drop policy.

3 packet by a packet that belongs to service-class 2 and 1 is realized with a probability $p_2 = 0.1$ and $p_1 = 0.2$, respectively. In Fig. 19 we present analytical PBP results of the three service-classes. As the results reveal, the PBP of the 3rd service-class is higher, compared to the PBP of the 1st and 2nd service-classes.

V. Conclusion

In conclusion, we propose analytical models for the calculations of PBP in an all-optical packet switch, under several QoS differentiation schemes. Packets that belong to multiple service-classes arrive from a finite number of input ports and attempt to gain access to an output wavelength. PBP is derived by the steady-state equation of one-dimensional Markov chains. The accuracy of the proposed calculations is quite satisfactory as was verified by simulations. In our future work we shall extend this analysis, in order to further study the effect of the implementation of FDLs and examine the deflection routing to the blocking performance of the all-optical switch.

Acknowledgment

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References

[1] J. S. Vardakas, I. D. Moscholios, and M. D. Logothetis, "An analytical Study of an All-Optical Packet Switch with QoS Support", in Proc. of the 6^{th} IARIA Advanced International Conference on Telecommunications - AICT 2010 , Barcelona, Spain, May 9-14, 2010.

[2] B. Mukherjee, "Optical WDM networks", Springer, 2006.

[3] N. Bouabdallah, "Sub-wavelength solutions for next generation optical networks", IEEE Communications Magazine, August 2007, pp. 36-43.

[4] R. V. Caenegem, D. Colle, M. Pickavet, P. Demeester, K. Christodoulopoulos, K. Vlachos, E. Varvarigos, L. Stampoulidis, D. Roccato, and R. Vilar, "The design of an all-optical packet switching network", IEEE Communications Magazine, November 2007, pp. 52-61.

[5] N. H. Harai, N. Wada, F. Kubota, and Y. Shinoda, "Multi-stage fiber delay line buffer photonic packet switch for asynchronously variable-length packets", IEICE Transactions on Communications, vol. E88-B, no. 1, January 2005, pp. 258-265.

[6] D. Hwrter, M. C. Chia, and Andonovic, "Buffering optical packet switches", IEEE/OSA Journal of Lightwave Technology., vol. 16, no. 12, December 1998, pp.2081-2094.

[7] S. L. Danielsen, P. B. Hansen, and K. E. Stubkjear, "Wavelength conversion in optical packet switching", IEEE/OSA Journal of Lightwave Technology, vol. 16, December 1998, pp. 20952108.

[8] V. Eramo and M. Listanti, "Packet loss in a bufferless optical WDM switch employing shared tunable wavelength converters", IEEE/OSA Journal of Lightwave Technology, vol. 18, December 2000, pp. 18181833.

[9] S. Yao, B. Mukherjee, S.J.B. Yoo, and S. Dixit, "A unified study of contention-resolution techniques in optical packet-switched networks", IEEE/OSA Journal of Lightwave Technology, vol. 21, no. 3, March 2003, pp. 672683.

[10] Z. Zhang and Y. Yang, "Performance modeling of bufferless WDM packet switching networks with limited-range wavelength conversion", IEEE Transactions on Communications, vol. 54. no. 8, August 2006, pp. 1473-1480.

[11] J. P. Jue, "An algorithm for loopless deflection in photonic packetswitched networks", in Proc. of IEEE International Conference on Communications, ICC 2002, vol. 5, New York, USA, 28 April - 2 May 2002.

[12] H. Øverby and N. Stol, "A teletraffic model for service differentiation in OPS networks", in proc. of the 8th Opto-electronic and Communications Conference, Shanghai, China, 13-16 October 2003, pp. 677678.

[13] H. Øverby, N. Stol and M. Nord, "Evaluation of QoS differentiation mechanism in asynchronous bufferless optical packet-switched networks", IEEE Communications Magazine, vol. 44, no. 8, August 2006, pp. 52-57.

[14] H. Øverby, and N. Stol, "QoS differentiation in asynchronous bufferless optical packet switched networks", Wireless Networks, vol. 12 no. 3, 2006, pp. 383-394.

[15] H. Øverby and N. Stol. "Quality of service in asynchronous bufferless optical packet switched networks", Telecommunication Systems, 27(24), 2004, pp. 151179.

[16] A. G. Fayoumi and A. P. Jayasumana, "A surjective-mapping based model for optical shared-buffer cross-connect", IEEE/ACM Transactions on Networking, vol. 15, no. 1, February 2007, pp. 226-233.

[17] V. Eramo, M. Listanti and R. Tiberio, "Performance evaluation of QoS-aware optical packet switches", in Proc. of IEEE International Conference on Communications (ICC 2008) , Beijing, China, 19-23 May 2008.

[18] H. Akimaru, K. Kawashima, "Teletraffic theory and applications", Springer-Verlag, 1993.

[19] Simscript II.5, http://www.simscript.com/