Effects of the switching time in OPS/OBS networks

Harald Øverby and Norvald Stol

Department of Telematics, Norwegian University of Science and Technology, O. S. Bragstadsplass 2E, N-7491 Trondheim, Norway

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In this paper we present an analytical model, which considers the effects of the switching time on the network performance in service differentiated optical packet/burst switching (OPS/OBS) networks. Our results indicate that the switching time must be less than 10 % of the packet/burst duration in order to avoid any significant reductions in the network performance. Furthermore, regarding a network with full wavelength conversion, we show that the benefits of statistical resource sharing are almost non-existent for low priority traffic when the switching time is large.

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In order to have a commercial viable deployment of a service differentiated optical packet/burst switching (OPS/OBS) network, the switching time is of great concern[1,2]. Since the switches in OPS/OBS are used to switch signals on a packet-by-packet basis (or burst-by-burst basis in the case of OBS), the switching time must be much smaller than the duration of the packet/burst. For example, the duration of a 500-byte packet on a 10-Gbit/s link is 400 ns, which means that the required switching time must be of some nanoseconds or less in order to avoid large reductions in the network performance. Most commercial available switches have switching times in the region of some milliseconds (e.g. MEMS switches and bulk mechanical switches), which do not satisfy the requirements for OPS/OBS[1]. However, fast switches such as semiconductor optical amplifier (SOA) switches (with switching time of some nanoseconds) and $LiNbO_3$ switches (with switching times of some picoseconds) are both promising technologies for OPS/OBS[1,2]. Our aim in this paper is first to develop an analytical framework and then discuss the effects of the switching time on the network performance in service differentiated OPS/OBS networks.

We consider an OPS network[3], but the results are also valid for the tell-and-go (TAG) OBS architecture (where the data burst immediately follows the burst control header)[4]. The effects of the switching time are addressed by considering a single output wavelength with capacity C (b/s) in an asynchronous optical packet switch with no internal blocking or wavelength conversion. As seen in Fig. 1, after a packet arrival (at time A_i), the switch must spend a fixed period of time equal to δ in idle modus before transmission starts (at time $A_i + \delta$). As δ increases relative to the packet duration, the switch spends an increased amount of time in idle modus, which results in poor resource utilization.

There are two service classes in the network, where service class 0 is given the highest priority and service class 1 is given the lowest priority (The authors of Ref. [5] argue for two service classes in the optical core network). We provide service differentiation by utilizing the preemptive drop policy (PDP), as presented in Ref. [6]. In the PDP, if the wavelength in our focus is free, new arrivals are transmitted independent of the service class of the arriving packet. However, if the wavelength is busy transmitting a class 1 packet, new class 1 packets are discarded, while new class 0 packets are allowed to interrupt the packet currently in transmission and take over (preempt) the respective wavelength for its own use. As part of the PDP we define and use a parameter q denoting the probability for successful preemption, i.e. with $q = 0$, we do not allow any preemptions (which refers to the best-effort scenario). On the opposite, with $q = 1$, new class 0 arrivals will succeed in every preemption attempt, assuming that there is a class 1 packet currently in transmission. Simulation results and detailed analysis based on time-continuous Markov chains regarding the PDP are found in Ref. [6].

In the following analysis we utilize the notations described in Table 1. We assume that packet inter-arrival times are exponential and identical, independent distributed (i.i.d.) with specified intensities equal to φ_i for service class i (i = 0, 1). Hence, the cumulative arrival rate distribution for service class i is given as $F_i(t) = 1 - e^{-\varphi_i \cdot t}$.

Initially, the packet length distribution (PLD) for packets in all service classes is assumed to be general and i.i.d. with density function $l_i(t)$ for service class i. This means that the transmission time distribution for service class i is $g_i(t) = l_i(t)/C$, and the mean transmission time for service class i is $E[G_i] = \int_{t=0}^{\infty} t \cdot g_i(t)\mathrm{d}t$. We now consider the effects of the switching time, where there is a fixed delay equal to δ between two subsequent packet transmissions. We model this by extending the transmission time

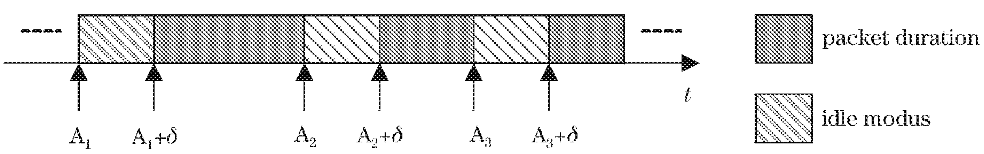

Fig. 1. The effects of the switching time δ.

Table 1. Notations Used in the Analysis

φ_i	Arrival Rate to the Output Wavelength from Service Class i
$F_i(t)$	Cumulative Arrival Rate Distribution from Service Class i
$l_i(t)$	Packet Length Distribution for Service Class i
$g_i(t)$	Transmission Time Distribution for Service Class i
$s_i(t)$	Service Time Distribution for Service Class i
ρ_i	Carried Traffic from Service Class i
P^i_{loss}	Packet Loss Rate for Service Class i
δ	Switching Time
q	The Probability for Successful Preemption
C	Link Capacity

to include δ before packet transmission starts. Hence, regarding service class i, the service time is composed of the switching time and transmission time, and its distribution is given as $s_i(t) = g_i(t)+\delta$. The mean service time is $E[S_i] = E[G_i]+\delta$. The offered traffic to the wavelength from service class i is given as $A_i = \varphi_i \cdot E[S_i]$. Hence, the carried traffic for service class i is the offered traffic minus the lost traffic, i.e.

$$\begin{aligned}\rho_i &= A_i - A_i \cdot P^i_{\text{loss}} \\ &= (1 - P^i_{\text{loss}}) \cdot \varphi_i \cdot E[S_i],\end{aligned} \tag{1}$$

where P^i_{loss} is the packet loss rate (PLR) for class i traffic.

We first calculate the PLR for service class 0 by considering a class 0 arrival to the output wavelength in our focus. In the PDP, we remember that class 0 traffic may preempt traffic from service class 1 with a probability q. However, if the wavelength is currently occupied transmitting class 0 traffic, new class 0 arrivals are lost. We obtain the PLR for class 0 traffic as

$$P^0_{\text{loss}} = \rho_0 + (1 - q) \cdot \rho_1. \tag{2}$$

We see that if $q = 1$ (i.e. a class 0 packet always preempt a lower class packet if possible), the PLR for class 0 traffic is just $P^0_{\text{loss}} = \rho_0$.

We now consider the PLR for class 1 traffic. First, class 1 traffic is lost if the wavelength is occupied transmitting class 0 or 1 traffic. If class 1 traffic is not rejected, it is (obvious) accepted and starts transmission. However, during transmission, class 1 traffic may be interrupted by class 0 traffic if there is a class 0 packet arrival before the class 1 packet has completed transmission. Again, the variable q denotes the probability for successful class 0 traffic preemptions. The integral $\int_\delta^\infty g_1(t - \delta) \cdot (1 - F_0(t))\mathrm{d}t$ gives the probability that the next class 0 arrival is arriving after the current class 1 packet has completed transmission. With reference to Fig. 1, we remember that if the class 1 packet arrives at A_1, it does not start transmission until $A_1 + \delta$. However, new class 0 packets may arrive at any moment after A_1. This leads us to the PLR for class 1 traffic as

$$\begin{aligned}P^1_{\text{loss}} &= (\rho_0 + \rho_1) + (1 - \rho_0 - \rho_1) \cdot q \\ &\quad \cdot \left[1 - \int_\delta^\infty g_1(t - \delta) \cdot (1 - F_0(t))\mathrm{d}t\right] \\ &= q + (1 - q)(\rho_0 + \rho_1) - (1 - \rho_0 - \rho_1) \cdot q \\ &\quad \cdot \int_\delta^\infty g_1(t - \delta) \cdot \mathrm{e}^{-\varphi_0 \cdot t}\mathrm{d}t.\end{aligned} \tag{3}$$

From Eqs. (2) and (3), if preemption is not available (i.e. $q = 0$), we see that the PLRs for service class 0 and 1 are equal, i.e. $P^0_{\text{loss}} = P^1_{\text{loss}}$.

In order to obtain numerical tractable expressions, we assume $q = 1$ and that the PLD from each service class is identical, i.e. $g(t) = g_i(t)$, which results in $E[G] = E[G_i]$, and $E[S] = E[S_i]$. We insert Eq. (1) into Eq. (2) and simplify to obtain the PLR for class 0 traffic as

$$P^0_{\text{loss}} = \rho_0 = (1 - P^0_{\text{loss}}) \cdot \varphi_0 \cdot E[S] = \frac{\varphi_0 \cdot E[S]}{1 + \varphi_0 \cdot E[S]}. \tag{4}$$

In order to obtain the PLR for class 1 traffic we insert Eq. (1) into Eq. (3), simplify, and obtain

$$\begin{aligned}P^1_{\text{loss}} &= 1 - (1 - \rho_0 - \rho_1) \cdot \int_\delta^\infty g(t - \delta) \cdot \mathrm{e}^{-\varphi_0 \cdot t}\mathrm{d}t \\ &= 1 - \left[1 - (1 - P^1_{\text{loss}}) \cdot \varphi_1 \cdot E[S] - \frac{\varphi_1 \cdot E[S]}{1 + \varphi_1 \cdot E[S]}\right] \\ &\quad \cdot \int_\delta^\infty g(t - \delta) \cdot \mathrm{e}^{-\varphi_0 \cdot t}\mathrm{d}t \\ &= \frac{1 - (1 - \rho_0 - \varphi_1 \cdot E[S]) \cdot \int_\delta^\infty g(t - \delta) \cdot \mathrm{e}^{-\varphi_0 \cdot t}\mathrm{d}t}{1 + \varphi_1 \cdot E[S] \cdot \int_\delta^\infty g(t - \delta) \cdot \mathrm{e}^{-\varphi_0 \cdot t}\mathrm{d}t}.\end{aligned} \tag{5}$$

First, from Eq. (4) we see that class 0 traffic is independent on the PLD, since only the first moment influences the PLR. However, in the case of class 1 traffic, we see in Eq. (5) that higher order moments influence the PLR, which means that the PLR is dependent on the PLD.

We further assume that the packets are exponential i.i.d., which means that $g_E(t) = \mu \cdot \mathrm{e}^{-\mu t}$ and $E[G_E] = \mu^{-1}$. The mean service time is $E[S_E] = E[G_E] + \delta = \mu^{-1} + \delta$. We obtain the PLR for class 0 traffic by substituting the expression for $E[S_E]$ into Eq. (4) and obtain

$$P^0_{\text{loss,exp}} = \frac{\varphi_0 \cdot E[S_E]}{1 + \varphi_0 \cdot E[S_E]} = \frac{\varphi_0 \cdot (\mu^{-1} + \delta)}{1 + \varphi_0 \cdot (\mu^{-1} + \delta)}. \tag{6}$$

The PLR for class 1 traffic is obtained by substituting the expression for $g_E(t)$ and $E[S_E]$ into Eq. (6). We integrate and obtain

$$P^1_{\mathrm{loss,exp}}$$

$$= \frac{1-(1-\rho_0-\varphi_1\cdot E[S_E])\cdot\int\limits_\delta^\infty \mu\cdot \mathrm{e}^{-\mu(t-\delta)}\cdot \mathrm{e}^{-\varphi_0\cdot t}\mathrm{d}t}{1+\varphi_1\cdot E[S_E]\cdot\int\limits_\delta^\infty \mu\cdot \mathrm{e}^{-\mu(t-\delta)}\cdot \mathrm{e}^{-\varphi_0\cdot t}\mathrm{d}t}$$

$$= \frac{1-\left(1-\rho_0-\varphi_1\cdot(\mu^{-1}+\delta)\right)\cdot\frac{\mu\cdot \mathrm{e}^{-\delta\cdot\varphi_0}}{\mu+\varphi_0}}{1+\varphi_1\cdot(\mu^{-1}+\delta)\cdot\frac{\mu\cdot \mathrm{e}^{-\delta\cdot\varphi_0}}{\mu+\varphi_0}}. \quad (7)$$

We define the switching time efficiency (STE) as the relative increase in the average PLR due to increased switching time as

$$\mathrm{STE}\,(h,c)=\frac{P^c_{\mathrm{loss}}|_{h>0}}{P^c_{\mathrm{loss}}|_{h=0}}, \quad (8)$$

where $h=\delta/\mu^{-1}$ is how large the switching time is relative to the packet/burst duration and c is the service class. In other words, the STE(h,c) measures how much the relative PLR increases compared to a situation with $\delta=0$ as a function of how large the switching time is relative to the packet/burst duration.

Simulations of an output wavelength according to the presented traffic model have been performed. Several independent simulations were performed and the average PLR was calculated. For all simulation results we have plotted the error-bars showing the limits within a 95 % confidence interval. Simulations have been obtained using the discrete event modelling on simula (DEMOS) software. The analytical results have been obtained from Eqs. (1)—(8). For all simulations the wavelength capacity is C = 10 Gb/s, the system load is 0.5, the variable $q=1.0$ and the relative share of class 0 traffic is $\varphi_0/(\varphi_0+\varphi_1)=0.2$.

Figure 2 shows the PLR as a function of the switching time δ when the mean burst length and transmission time is 40 kbytes and $E[G_E]=32$ μs, respectively (reflecting the OBS architecture employing the TAG scheme with variable sized bursts[4]). First, we see that the analytical results match the simulation results. However, although it is barely noticeable in Fig. 2, for some values of the switching time, there is a bias between the analytical and simulation results. This is because the analytical results assume a work conservative system; while in the simulations there is a loss of work, which contributes to an increased PLR for both service classes (see Ref. [7] for a precise definition of the term 'work conservative' in this context). Hence, the analytical results slightly underestimate the PLRs for both service classes.

Furthermore, when δ becomes relative large compared to the packet/burst duration, the PLR is heavily affected and will eventually converge to 1.0. This is because the switch spends almost all of its time in idle modus and is thus incapable of transmitting packets.

Figure 3 plots the STE as a function of h for two different spans of h. From Fig. 3(a), we see that the PLR increases with 10% when the STE = 1.1 (i.e. the switching time is 10% of the packet duration). This means that the switching time must be $\delta<3.2$ μs in the case of $E[G_E]=32$ μs. Hence, since large bursts require slower switching times in the switch compared to short packets, the OBS architecture is a promising candidate for the next generation optical core network. On the other hand, as stated in Ref. [8], due to the problems of realising fiber delay line (FDL) buffers that can support

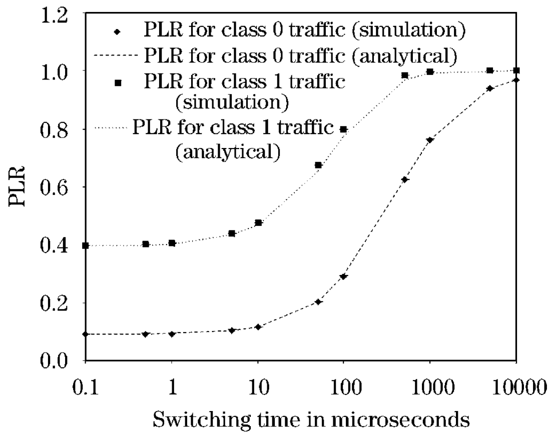

Fig. 2. The PLR as a function of the switching time in the case of exponential i.i.d. packets.

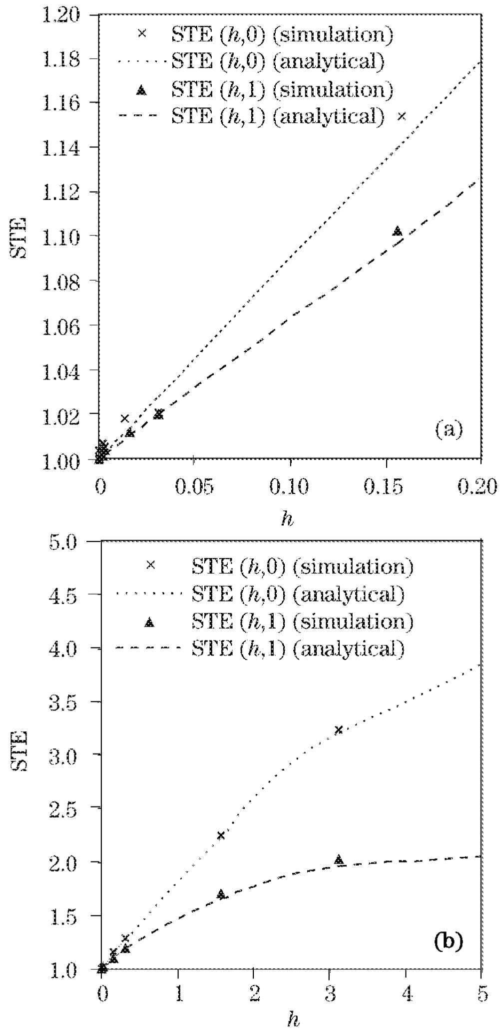

Fig. 3. The STE as a function of h for two different ranges of h.

large bursts (because of signal degradation), it is not feasible to use bursts in the order of several Mbytes in OBS with FDL-buffering. From Fig. 3(b), we see that $\mathrm{STE}(h,0) > \mathrm{STE}(h,1)$, which means that class 0 traffic is more influenced by an increased switching time compared to class 1 traffic.

We now consider the effects of the switching time in a network with full wavelength conversion. The fibre has several wavelengths to transport data, each with a capacity of $C = 10$ Gb/s. In Fig. 4, we show the PLR when the switching time is neglected (i.e. $\delta = 0$ and $h = 0$), and in the case of a switching time $\delta = 50$ μs ($h = 1.56$), as a function of the number of wavelengths. First, considering the case with $\delta = 0$, we see that the PLR decreases as the number of wavelengths increases, which is due to the effects of statistical resource sharing. Even though the load per wavelength is the same, a larger number of available resources give better performance[9]. This benefit pass for both class 0 and class 1 traffic. Second, considering the case with $\delta = 50$ μs, we see that the PLR

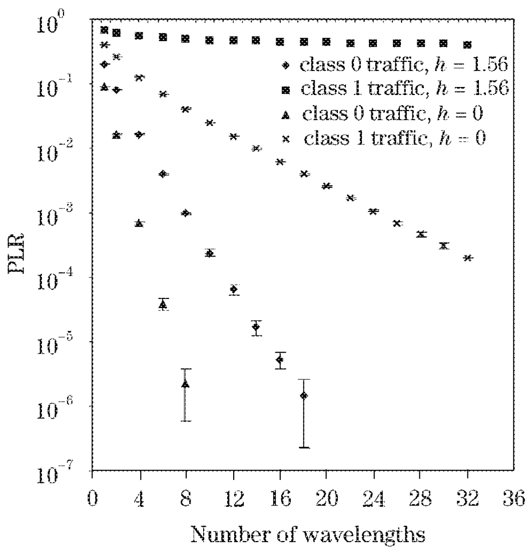

Fig. 4. The PLR as a function of the number of wavelengths in a switch with wavelength conversion.

for class 0 traffic decreases as the number of wavelengths increases. However, the PLR for class 1 traffic is almost constant when the number of wavelengths increases (in fact, there is a small reduction, but it is barely visible in Fig. 4). These results indicate that class 1 traffic does not benefit from statistical resource sharing in any particular degree under the presence of a large switching time.

At last, we see that only the SOA switches (with switching time of approximately 1 ns[1]) and the $LiNbO_3$ switches (with switching time of approximately 10 ps[1]), can satisfy the switching time requirements for this scenario, which is in accordance with results from previous research[2]. Also, according to Ref. [2], of these two switches the SOA is the most promising since the $LiNbO_3$ switches are driven by large voltage and have large insertion loss and large crosstalk.

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