Evaluation of Optical Burst-Switching as a multiservice environment

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Abstract. We propose a scheme for providing differentiated services in an optical burst switching network environment. Our framework considers differentiation among several traffic classes in packet loss probability, assuming only that the network differentiates neatly between two classes of bursts. We formulate a reduced load fixed point model for evaluating the blocking probabilities of the different types of bursts. The model is the basis to compare several flavors of OBS in terms of ability for achieving quality of service. Motivated by technological constraints, we investigate the effect of wavelength density on its performance.

1 Introduction

[1] In optical burst switching networks (OBS), the data transport plane and the control plane are fully decoupled, both in time and space [1]. Packets are assembled at access nodes according to destination, class or quality of service, and form bursts to be entered into the optical core. Within the signaling plane, a control packet is sent ahead of the burst along the same path so as to reserve the necessary resources inside the core nodes. After a delay, the data burst is sent along the all-optical path set by the prior reservation. However, control packets are not acknowledged, and a burst may be discarded owing to contention with other bursts at the bufferless optical switches.

Though this description grabs the essential operations of OBS networks, there exist a number of possibilities regarding how the access nodes and the switches actually work. First, bursts can be assembled according to many different criteria, and their statistical and temporal behavior (length, time variability, correlation), in addition to the routing strategy, turn out to be paramount factors in determining the degree of contention at the optical switches [2]. Moreover, such contention can be managed in several different ways by means of proper burst scheduling [3, 4]. Thus, the scheduling algorithm running in the nodes has a strong influence in the probability of the bursts being successfully transmitted to their destination [5, 6] and in the provision of quality of service (QoS) to

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the bursts and the data packets conveyed within them [7, 8]. Included among the mechanisms conceived to enhance the performance of OBS networks are segmentation (i.e., splitting the burst into smaller independent units [9, 10]), deflection (i.e., rerouting of bursts in conflict [11]), or the use of different time offsets [12]. If carefully engineered, these algorithms are all capable of providing some degree of QoS in terms of burst blocking probability, at least for underloaded networks.

Given this variety of approaches to support QoS inside OBS, the question we ask in this paper is whether the differentiation offered to the optical bursts can be exploited outside the optical domain. In real networks, OBS is likely to be deployed incrementally, coexisting with electronic packet switching. We show that it is possible to differentiate *proportionally* in *packet loss probability* among several classes of traffic arriving to the access nodes, provided only the OBS network offers two widely separated blocking priorities at the burst level. The particular scheduler used in the optical nodes plays a secondary role in this architecture. In order to bind burst blocking and packet loss probability, we propose a scheme based on a probabilistic classification of packets into high and low priority bursts. For the performance analysis of this system, a general reduced load fixed-point model for the OBS network is developed. The model accounts for networks with any number of internal traffic classes and two control-plane OBS variants, and can easily incorporate different scheduling algorithms in the nodes. In fact, we take an abstract view of the algorithm, and analyze two broad classes of general schedulers which include many of the former as particular cases. By solving the system model for three simple topologies, the region of feasible differentiation is evaluated. Specifically, given a combination of scheduler, topology and transmission resources, the blocking probabilities for all the priority classes of end-to-end burst flows are computed, and the QoS capabilities of this architecture are elucidated.

The paper is organized as follows. Section 2 describes the proportional differentiated services scheme. In Section 3 we formulate the general fixed point approximation for a two priority OBS network. Section 4 explains how to incorporate into the model the scheduling algorithm, and Section 5 states the cases of full meshes, star and ring topologies. In Section 6 the model is used to analyze the differentiation capabilities of the proposed scheme as a function of the scheduling algorithms, the network topology and the density of the WDM links in the OBS network. We summarize our conclusions in Section 7.

2 The packet differentiation algorithm

Suppose that N classes of packets are offered to an OBS network. We aim to provide differentiated services in such a way that the packet loss probability (PLP) of any two classes i and j satisfies

$$\frac{p_i}{p_j} = \frac{c_i}{c_j}$$

where c_x is an arbitrarily assigned coefficient that measures the class' quality of service. Assume also that the transport network differentiates between two classes of bursts, say type 0 and type 1 bursts, in such a way that the loss probability of packets transported in type 0 bursts (respectively, 1) is B_0 (B_1), where $B_0 \ll B_1$. If packets of class x are assembled into type 1 bursts with probability h_{x1}, and into type 0 bursts with probability $1 - h_{x1}$, then the ratio of PLP between classes $i, j \in \{1, \ldots, N\}$ is

$$\frac{p_i}{p_j} = \frac{(1 - h_{i1})B_0 + h_{i1}B_1}{(1 - h_{j1})B_0 + h_{j1}B_1}. \tag{1}$$

Under the assumption $(1 - h_{i1}) \cdot B_0/B_1 \ll 1$, this becomes $p_i/p_j \simeq h_{i1}/h_{j1}$ that is, the packet loss ratio is approximately the ratio of two arbitrarily chosen constants. Consequently, by varying the fraction of packets of each class transmitted through the underlying classes of bursts it is possible to provide proportional loss probabilities. The range of feasible differentiations with this probabilistic scheme is bounded by the case in which one packet class goes entirely through the low priority (type 1) bursts, and the other class is always assigned to the high priority bursts, giving a maximum differentiation power of $p_i/p_j|_{\max} \simeq B_1/B_0$. For any number of packet classes and its corresponding set of differentiation factors, set B_1/B_0 equal to the ratio between the largest and lowest coefficient. It is worthy of mention that the probabilistic mapping of several external traffic classes into two internal transport levels is easy to incorporate into the network equipment, and is independent of any technology, so it could be used at the edge of any core network, either OBS or not.

3 System model for the OBS network

We shall use a fixed point model [13] to analyze and dimension an OBS network with service differentiation capabilities. Fixed point models have been widely used in the circuit-switching world, in packet switching environments and in OBS to analyze the fundamental performance of those networks [14],[15]. In this work, we assume that the rate at which sources generate packets is independent of the state of the network, therefore having an open-loop system. The case in which sources are responsive to the network state can be treated by extending the system model with the equations that capture the dependency between data rate generation and network state [16], and is left for further study. One feature explicitly included is the use of different burst schedulers.

Consider an OBS network with L links, N nodes with full wavelength conversion and two internal types of bursts. Each link l is unidirectional having capacity C_l. Let $\mathcal{R}$ be the set of routes in the network, $\alpha \in \mathcal{R}$ an origin-destination pair, and (x, α) a Poisson process modeling the priority x burst arrivals to route α, with rate $\lambda_{(x,\alpha)}$. Each burst will attempt to reserve in each node along its path a time S dependent on the scheduling discipline at use in the node. For example, in JET mode, each burst uses the resource for L/C time units, where L is the burst length and C is the capacity of each wavelength in the WDM network, whereas in JIT [17] the reservation interval begins with the arrival of the control packet, and its length equals the offset plus the burst transmission time, so $S^{\mathrm{JET}} = \frac{L}{C}$, and $S^{\text{JIT}} = \text{Offset} + \frac{L}{C}$. Hence, each policy p , $p \in \{\text{JET}, \text{JIT}\}$ will induce an offered traffic intensity $A^p_{(x,\alpha)} = \lambda_{(x,\alpha)} \cdot S^p_{(x,\alpha)}$.

Denote by A_{xl} and B_{xl} the offered traffic intensity and blocking probability of class x bursts at link l, respectively. Then, the implicit solution of the following fixed point system

$$A_{xl} = \sum_{r \in \mathcal{R}} A^p_{x,r} I_{r,l} \prod_{i=1}^{o(l,r)-1} (1 - B_{xi_r}) \,, \qquad B_{xl} = \Lambda(A_{0l}, A_{1l}) \tag{2}$$

gives the vector $\Phi_x = (B_{x1}, B_{x2}, \ldots, B_{xL})$ of blocking probabilities for class x at the L links in an arbitrary network. $I_{r,l}$ (1 if link l belongs to route r; 0, otherwise) is the $|\mathcal{R}| \times L$ topology matrix of the network, $o(l, r)$ is the ordinal of link l in route r, i_r is the i-th link of route r, and $\Lambda(\cdot, \cdot)$ is a mapping giving the losses for each class as a function of the offered load, the capacity of link l and the local scheduling algorithm.

Note that the load offered to link l includes the sum from the whole set of routes traversing that link. In the system model, the traffic contributed by route α is approximated as a Poisson process with intensity $\lambda_{(x,\alpha)}$ thinned by the losses in the links preceding l along that route. This approximation is more accurate as the degree of connectivity of the network increases. Note also that the model has been formulated only for two classes of bursts, but the generalization to an arbitrary number of traffic classes is straightforward. After solving for the link blocking probabilities, the blocking probability of bursts of class x in route r is simply $B^r_x = 1 - \prod_{i \in r} (1 - B_{xi})$.

4 The scheduling algorithms

Each scheduling algorithm defines a functional form Λ for the losses suffered by both classes of bursts. For instance, if Λ was the Erlang-B formula and the network had only one traffic class, the model would be equivalent to the Erlang fixed point approximation for an OBS network. However, we are interested in analyzing more general architectures, and focus in this section on two scheduling policies, namely a system with fixed priorities and preemptive service, and a system with time-dependent priorities based on an occupancy threshold.

4.1 Preemptive priorities

Assume class 0 bursts are given preemptive priority over class 1 bursts. Thus, a control packet for a burst that has been preempted continues to reserve resources for a burst that no longer exists, with the possibility of blocking other class 1 bursts that actually contain data. Following [18], this kind of scheduler can be modeled as if class 0 bursts were unaffected by the others and approximating the blocking probability of the combined traffic as that resulting from the aggregate offered load. Such model does not take into account the effect of the preemptions, so it is expected to produce good estimations in low load regimes. Therefore, $B \simeq E_B(A_0 + A_1, \mathsf{m})$, $B_0 = E_B(A_0, \mathsf{m})$ and

$$B_1 \simeq \frac{B - \beta_0 B_0}{1 - \beta_0} \triangleq E_{LP}(A_0, A_1, \mathsf{m})$$

with $\beta_0 = \frac{\lambda_0}{\lambda_0 + \lambda_1}$ the fraction of class 0 bursts arrivals.[2] The PLP will in general be different than the blocking probability for bursts if the latter depends on the bursts' length. This will not happen if the assembler produces fixed length bursts and, depending on the specific scheduler being in use at a node, if the offsets of the bursts arriving at that node are the same. But the assumption of constant offsets does not hold for the scheduler being described in this section. Nevertheless, given that the difference between the two quickly diminishes with the number of output channels in this scheduler [19], we will approximate the loss probability of a packet by the blocking probability of its burst type.

4.2 Threshold-induced priorities

An alternative method for establishing priorities between bursts could be the use of a threshold u such that if the number of reserved resources when a burst of low priority is due to arrive is higher than the threshold, the burst is blocked. In this case, the blocking probabilities of both classes depend on the traffic intensities of the two classes [20], and are given by $B_0 = P(\mathsf{m})$, $B_1 = \sum_{i=u}^{\mathsf{m}} P(i)$, with

$$P(i) = \begin{cases} \frac{(A_0+A_1)^i}{i!} P(0) & i \in [1, u] \\ (A_0 + A_1)^u \frac{A_0^{i-u}}{i!} P(0) & i \in [u+1, \mathsf{m}] \end{cases}$$

and $P(0)$ the normalizing constant such that $\sum_{i=0}^{\mathsf{m}} P(i) = 1$. This is an appealing scheme for implementing priorities, since it offers the possibility of dynamically adjusting the threshold in response to changes in the network state.

5 Modelling the topology

The system model (2) can be explicitly rewritten for simple topologies. Let us consider here three cases.

5.1 Full mesh OBS network

The network is composed by N nodes fully connected in pairs, with m wavelengths per link. The traffic intensities in each possible origin-destination pair are A_0 and A_1. In a full mesh, every link is a single route, and its blocking probability depends only on the offered traffic A_{xl}. If the OBS nodes use the preemptive

[2] Throughout the paper, E_B is the Erlang-B formula, m is the number of wavelengths on link l and E_{LP} stands for the blocking probability of low priority bursts.

scheduler, then $A_{xl} = (N-1)A_x$, $B_{0l} = E_B(A_{0l}, \mathsf{m})$, and $B_{1l} = E_{LP}(A_{0l}, A_{1l}, \mathsf{m})$. Since all routes have one-link paths, B_0 and B_1 are the blocking probabilities in the route under consideration.

5.2 Star OBS network

Consider now a network composed of N core nodes connected through one additional core node by means of bidirectional links with m wavelengths per direction. There are M edge nodes connected through high-capacity links (no losses in the link going from the edge to the core) to each of the N external core nodes. Assuming that routes between two edge nodes connected to the same core node do not exist, and that there is the same traffic intensity between each pair of edge nodes for each priority, then there are two points where a burst can be blocked, the link going from its nearer core node to the central switch, and the link from the central switch to the destination core. Denote by A_{x1}, A_{x2}, B_{x1} and B_{x2} the intensities and blocking events of class x bursts offered to those two links. Then, with the preemptive scheduler, we have $A_{x1} = (N-1)M^2 A_x$, $A_{x2} = A_{x1} \cdot (1 - B_{x1})$, and blocking probabilities

$$B_{01} = E_B(A_{01}, \mathsf{m}), \quad B_{11} \simeq E_{LP}(A_{01}, A_{11}, \mathsf{m})$$
$$B_{02} \simeq E_B(A_{02}, \mathsf{m}), \quad B_{12} \simeq E_{LP}(A_{02}, A_{12}, \mathsf{m}).$$

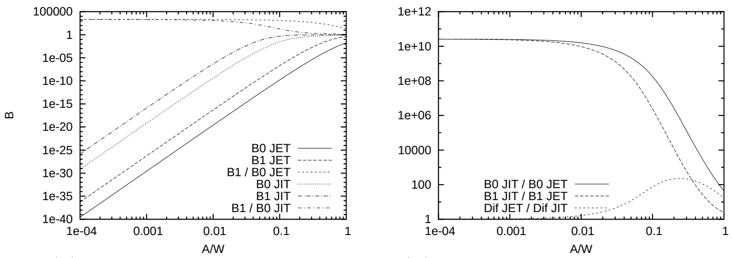
Finally, the end-to-end blocking probability for a burst of class x will be $B_x = 1 - (1 - B_{x1})(1 - B_{x2})$.

5.3 Ring OBS network

This network is a ring of N core nodes connected by bidirectional links, where M edge nodes are connected to each core node through high-capacity links, as before, and there is no traffic between two edges from the same core. If there is traffic between every pair of edges for each priority, and shortest-path routing is used, then, for N odd the offered load to each link in the ring is the same, by symmetry. Consequently, $A_{xl} = M^2 A_x \sum_{i=0}^{\lfloor \frac{N}{2} \rfloor - 1} \left(\lfloor N/2 \rfloor - i\right)(1 - B_{xl})^i$, and $B_{0l} = E_B(A_0, \mathsf{m})$, $B_{1l} = E_{LP}(A_0, A_1, \mathsf{m})$. The blocking probability of class-x bursts that traverse a path of L hops in the ring is given by $B_x = 1 - (1 - B_{xl})^L$ for $L = 1, \ldots, \lfloor N/2 \rfloor$.

6 Differentiation performance

In this section we use the model to provide guidelines for the topology design and configuration of a service-differentiation enabled OBS network in several useful scenarios: full mesh, star, ring and mesh topologies.



(a) preemptive scheduler (b) threshold-based scheduler

Fig. 1. Blocking probabilities and differentiations in a full mesh

6.1 Full mesh

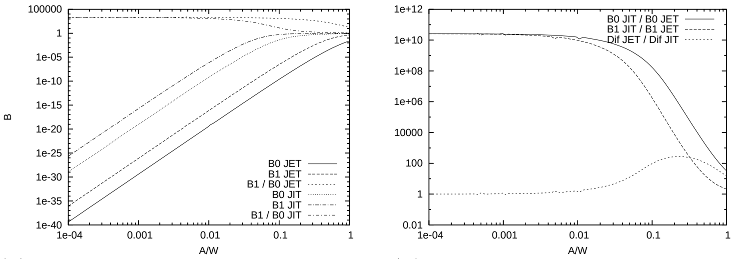
We begin with the case of a fully connected network of core nodes, each one also connected to several edge nodes. Fig. 1(a) depicts the loss probabilities of both burst classes as a function of the link load, in when the offered traffic from both priorities is the same. This configuration uses 10 wavelengths per link, an offset of 10 ms, an average burst size of 0.1 s and the preemptive scheduler.

The first observation is that JIT has higher blocking than JET for all bursts, as a result of having a higher demand for wavelength reservation than JET for a burst of a given size. The proportional differentiation is the same for both schemes in the low load region, until losses in the JIT case approaches unity — some two orders of magnitude sooner than JET, when the load is around 0.01. With m wavelengths and a traffic intensity ratio $A_1/A_0 = K$, the differentiation B_1/B_0 in the low load region has an asymptotic value

$$D \triangleq \lim_{A_0 \to 0} \frac{E_{LP}(A_0, KA_0, \mathsf{m})}{E_B(A_0, \mathsf{m})} = \frac{(1+K)^{\mathsf{m}+1} - 1}{K}.$$

In this case $K = 1$, so $D = 2047$, which is what we see in the figure. This result may be used to dimension the network under the constraint of a desired maximum differentiation for the packets of the external classes. Having in mind that the network load must be low, this approach could be coupled with some form of admission control to effectively ensure the desired differentiation. Regarding prorportional differentiation, JET and JIT are similar until the load approaches the high loss region for JIT, with the result that at medium loads JET performs better for the packets of the external classes.

Figure 1(b) shows the results using a threshold-based scheduler with a threshold of 5 wavelengths. Now, the behavior at low loads is dependent on the absolute value of the load: the largest differentiation achievable for the external traffic decreases with the load. Thus, JIT and JET show different proportional differentiation levels, with JET achieving much better differentiation between high and low priority bursts. ombining no wavelength conversion in the node with the preemptive scheduler, the behavior is the same as with wavelength conversion, but the blocking probabilities are much larger. In this case we have that



(a) Blocking probabilities and differentiations

(b) Proportional differentiation

Fig. 2. Ring topology with preemptive scheduler

the asymptotic differentiation in the low load case is

$$\lim_{A_0, A_1 \to 0} \frac{E_{LP}(A_0, A_1, \mathsf{m})}{E_B(A_0, \mathsf{m})} = K + 2.$$

which is substantially lower (near 3) than with wavelength conversion (2047). Incidentally, though not shown, the results for a star topology are very similar to the full mesh, albeit with slightly larger blocking probabilities.

6.2 Ring

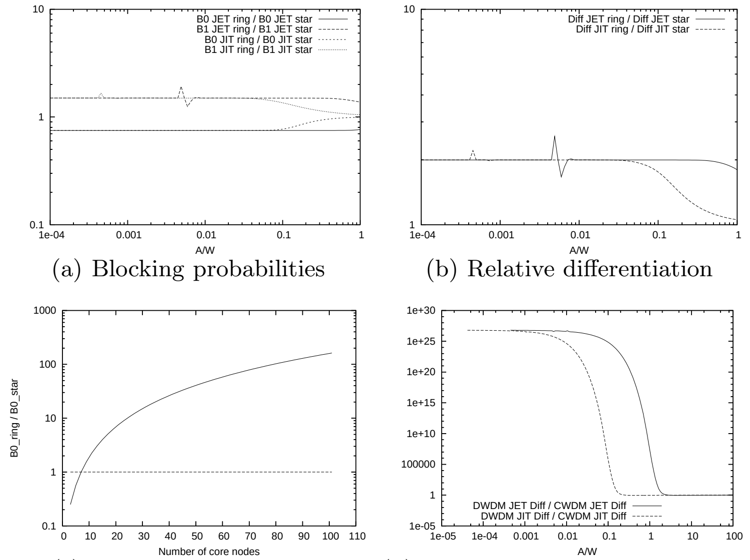
In this case we consider a ring network with 4 core nodes and 5 edge nodes connected to each core node. The results for this configuration are shown in Figs. 2(a) and 2(b). In these plots, B_0 or B_1 refer to the average blocking probabilities from all routes. The behavior is remarkably similar to the star topology, and Figures 3(a) and 3(b) display a comparison between both cases.

In the former, the blocking probabilities in the ring for the high priority class are around 0.75 times the ones for the star, so it appears that connecting the nodes as a ring in this specific scenario offers advantages from the point of view of absolute blocking for the high priority class; the ring topology also has a higher blocking for the low priority class, so regarding the proportional differentiation (Fig. 3(b)) the ring performs better than the star.

In a more general case, the comparison between the ring and star topologies can be made explicit using our model. In the low load region, the ratio between the blocking of high priority bursts in rings and stars as a function of the number of nodes in the network, denoted by ρ, is[3]

$$\rho = \lim_{A_0 \to 0} \frac{B_0^{\text{ring}}}{B_0^{\text{star}}} \simeq \frac{1}{8} \frac{(\lfloor \frac{N}{2} \rfloor + 1)^2}{N-1} \lfloor \frac{N}{2} \rfloor.$$

[3]This comes from $B_0^{\text{star}} = E_B\left((N-1)M^2 A_0, \mathsf{m}\right) + E_B\left((N-1)M^2 A_0(1-B_0), \mathsf{m}\right)$ and $B_0^{\text{ring}} = E_B\left(M^2 A_0 \sum_{i=0}^{\lfloor N/2 \rfloor - 1} \left(\lfloor N/2 \rfloor - i\right)(1-B_x)^i, \mathsf{m}\right)\overline{L}$, where $\overline{L} = (\lfloor N/2 \rfloor + 1)/2$ the mean number of hops of a path in the ring.



(a) Blocking probabilities (b) Relative differentiation

(c) Number of core nodes (d) Coarse vs. dense DWDM, ring

Fig. 3. Comparison between star and ring topologies

Thus, the ratio does not depend on the number of edge nodes, M. It only depends on the number of core nodes, N, and we plot this dependence in Figure 3(c). It rapidly increases with N; for low values of N the ring is better, and for high values of N the star is better; the point at which the two topologies are the same is around 5. So we can conclude that if the number of core nodes to connect in some topology is lower than 6, then the ring topology is preferable over the star topology in terms of the blocking probabilities. Of course, in the star configuration with large numbers of nodes, the central node must have enough processing power for handling all the traffic in the network.

6.3 Coarse WDM and Dense WDM

Next, we study how the differentiation capability is affected by the presence of more wavelengths in the links. Assuming we have full wavelength conversion and focus on the ring topology, we see in Figure 3(d) the comparison between two architectures, one with 10 wavelength links and another with 100 wavelength links. The DWDM system has superior differentiation capabilities than the CWDM system. The difference between 10 an 100 wavelengths accounts for a growth of some 27 orders of magnitude in the ratio of burst blocking probabilities for bursts of each type.

It is also possible to use the model to approximate the differentiation gain between two scenarios with the preemptive scheduler, one with m wavelengths per link and another with $L \cdot \mathsf{m}$ wavelengths per link. Assuming low traffic load in the links, the blocking probabilities should also be also, so we can approximate the end-to-end blocking probability with the sum of probabilities in the traversed links. Moreover, since blocking probabilities are small, we approximate the offered intensities in all links as the original ones, so the blocking probability for one class of bursts is equal to a constant number of times the blocking on one link. Thus, the network can be approximated by the full mesh case, and if we denote $D(x)$ the proportional differentiation in blocking probability between the two classes of bursts when there are x wavelengths in a link, we have

$$\lim_{A_0 \to 0} \frac{D(L\mathsf{m})}{D(\mathsf{m})} = \lim_{A_0 \to 0} \frac{(1+K)^{L\mathsf{m}}}{(1+K)^{\mathsf{m}}} = (1+K)^{(L-1)\mathsf{m}}$$

With a scenario of 10 and 100 wavelengths ($L = 10$) and same traffic intensities for both priorities ($K = 1$), the ratio of possible maximum differentiations is in the order of $(1+1)^{9 \cdot 10} \simeq 10^{27}$, and that is what we observe in Figure 3(d).

7 Discussion and Conclusions

The motivation in this work has been to analyze the region of feasible differentiations in burst blocking probability of OBS networks supporting two internal types of bursts. In the course of that characterization, we have developed an analytical model useful for dimensioning any OBS network in order to be able to offer differentiated services in blocking probability to several external classes of packets. The model also helps in the task of analyzing the effect of the scheduler algorithm running at the nodes and in choosing a suitable topology and OBS policy. There are some remarkable conclusions drawn from the numerical studies. First, dense WDM offers a substantial advantage over coarse WDM with respect to loss probability differentiation for the same traffic mix. Also, wavelength conversion at the switches (either partial or total) plays a vital role for achieving low blocking probabilities for any amount of offered traffic, and therefore it is a necessary function in the proposed QoS architecture. Finally, there is a clear difference in the capacity of the OBS network between the different control planes. For moderate values of the blocking probability, JET outperforms JIT in approximately two orders of magnitude in the throughput.

References

1. C. Qiao and M. Yoo, "Optical burst switching (OBS) - a new paradigm for an optical internet," *Journal of High Speed Networks*, vol. 8, no. 1, pp. 69–84, 1999.
2. X. Yu, J. Li, X. Cao, Y. Chen, and C. Qiao, "Traffic statistics and performance evaluation in optical burst switched networks," *Journal of Lightwave Technology*, vol. 22, no. 12, pp. 2722–2738, 2004.
3. J. Xu, C. Qiao, J. Li, , and G. Xu, "Efficient burst scheduling algorithms in optical burst-switched networks using geometric techniques," *IEEE JSAC* , vol. 22, no. 9, pp. 1796–1811, 2004.

4. C. Gauger, M. Kohn, and J. Scharf, "Comparison of contention resolution strategies in OBS network scenarios," in *Proceedings of the 6th International Conference on Transparent Optical Networks*, Wroclaw, Poland, July 2004, pp. 18–21.
5. N. Barakat and E. Sargent, "An accurate model for evaluating blocking probabilities in multi-class OBS systems," vol. 8, no. 2, pp. 119–121, 2004.
6. M. Yoo, C. Qiao, S. Dixit, "QoS performance of OBS in IPoWDM networks," *IEEE J. Select. Areas Commun.*, vol. 18, no. 10, pp. 2062–2071, 2000.
7. ——, "Optical burst switching for service differentiation in the next-generation optical internet," *IEEE Commun. Mag.*, vol. 39, no. 2, pp. 98–104, 2001.
8. Q. Zhang, V. Vokkarane, J. Jue, B. Chen, "Absolute QoS differentiation in optical burst-switched networks," *IEEE JSAC.*, vol. 22, no. 9, pp. 1781–1795, 2004.
9. V. Vokkarane and J. Jue, "Prioritized burst segmentation and composite burst-assembly techniques for QoS support in optical burst-switched networks," *IEEE J. Select. Areas Commun.*, vol. 21, no. 7, pp. 1198–1209, 2003.
10. M. Neuts, Z. Rosberg, H.L. Vu, J. White, M. Zukerman, "Performance analysis of optical composite burst switching,"*IEEE Comm. Lett.*, v.6, n.8, p.346-348, 2002.
11. A. Zalesky, H. L. Vu, Z. Rosberg, E. Wong, M. Zukerman, "Modelling and performance evaluation of optical burst switched networks with deflection routing and wavelength reservation," *INFOCOM 2004*, Hong Kong, 2004, pp. 1864–1871.
12. N. Barakat, E. Sargent, "Analytical modeling of offset-induced priority in multiclass OBS networks," *IEEE Trans. Comm.*, vol. 53, no. 8, pp. 1343–1352, 2005.
13. F. P. Kelly, "Blocking probabilities in large circuit-switched networks," *Advances in Applied Probability*, vol. 18, no. 2, pp. 473–505, 1986.
14. Z. Rosberg, H. L. Vu, M. Zukerman, J. White, "Performance analyses of optical burst-switching networks," *IEEE JSAC*, vol. 21, no. 7, pp. 1187–1197, 2003.
15. K. W. Ross, *Multiservice Loss Models for Broadband Telecommunication Networks.* London,UK: Springer-Verlag, 1995.
16. J. Padhye, V. Firoiu, D. Towsley, and J. Kurose, "Modeling tcp reno performance: a simple model and its empirical validation," *IEEE/ACM Trans. Networking*, vol. 8, no. 2, pp. 133–145, 2000.
17. I. Baldine, G. Rouskas, H. Perros, and D. Stevenson, "JumpStart: a just-in-time signaling architecture for WDM burst-switched networks," *IEEE Commun. Mag.*, vol. 40, no. 2, pp. 82–89, 2002.
18. H. L. Vu and M. Zukerman, "Blocking probability for priority classes in optical burst switching networks," *IEEE Commun. Lett.*, vol. 6, no. 5, pp. 214–216, 2002.
19. P. Argibay-Losada, A. Suárez-González, M. Fernández-Veiga, R. F. Rodríguez-Rubio, and C. López-García, "From relative to observable proportional differentiation on OBS networks," in *Proc. ACM Conference on Emerging Network Experiment and Technology (CoNEXT'05)*, Toulouse, France, Oct. 2005, pp. 115–123.
20. M. Schwarz, *Telecommunication Networks.* Addison-Wesley, 1988.