Performance Overview of the Offset Time Emulated OBS Network Architecture

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***Abstract*—Optical burst switching (OBS) control architecture considers two different models for the management of the offset time in the network. The conventional OBS (C-OBS) introduces the offset time in soft-way by delaying the transmission of the burst relative to its control packet in the edge node. Another idea for an OBS architecture (E-OBS) comes from optical packet switching world and it intends to emulate offset time by means of an additional fiber delay unit introduced in the data path at the input port of the nodes. Although C-OBS has attracted lots of attention, in this paper we highlight that it possesses many difficulties that can be entirely removed in E-OBS. Issues such as unfairness in resource reservation, efficiency and complexity of burst scheduling, difficulty with alternative and backup routing, and quality of service (QoS) provisioning are studied. Moreover, E-OBS facilitates the application of several enhanced mechanisms. As an example, in this paper we analyze a QoS application based on a preemption window mechanism, which expands look-ahead processing window technique to the burst preemption context. Results show that this mechanism can achieve the performance of the conventional preemption scheme while avoiding the well-known problem of phantom burst generation.**

***Index Terms*—Network architecture, offset time provisioning, optical burst switching (OBS), quality of service (QoS) provisioning.**

I. Introduction and Motivations

THE principal objective of an optical burst switching (OBS) [1] network is the provisioning of statistical multiplexing in optical domain so that the wavelength resources can be used temporarily and shared between different users. This feature can increase the network scalability and adaptability to the bursty characteristics of IP traffic. The separation of control and data channels in OBS improves the network control and management, and provides additional flexibility such as for instance the possibility to use different modulation formats and data rates. Moreover, the aggregation of user data helps to reduce the scale of control information processed in the network as well as it relaxes switching requirements.

Other motivation for the OBS technology comes from the network user side. Yet not long ago the predictions on expected services concerned mainly a meaningful participation of real-time multimedia applications with streaming video and broadcasted TV services in packet networks. Instead, the recent dominance of P2P multimedia and data file transfers (e.g., MP3/divx) has modified previous goals somewhat [2]. The matter to users now is getting a quite big of bits quickly, with low transaction latency. With such P2P services, the typical methods being planned for controlling networks may not fit to the user expectations. The OBS concept of dynamic optical transmission and arbitrarily long data bursts seems to match to these demands well.

Similar objectives of high bandwidth, dynamic, fast, and usually long-distance and configurable granularity transmission provisioning are in the cloud computing environment. Cloud computing is an emerging approach to distribute a collection of heterogeneous computational, storage, network resources, and services over Internet [3]. Most of current operations (derived from grid networks [4]) are dedicated to a limited set of computationally and/or data intensive scientific problems, like, e.g., high energy physics, weather forecast or high-performance computing and visualization. The adoption of service oriented architectures and Web 2.0 applications is driving the implementation of large cloud computing infrastructures in the near future. The flexibility of the network operation and the huge optical capacity of the OBS technology are appropriate characteristics for such infrastructure and applications.

In an OBS network, the wavelength is booked temporarily on-the-fly by means of control information—referred hereafter as a *burst control packet* (BCP). The BCP is transmitted out-of-band and delivered to the core nodes with some offset time prior to the data burst—usually referred simply as a *burst*. The offset time provides the necessary time budget for both the processing of the BCP in an electronic switch controller and the reconfiguration of an optical switching matrix, so that to route the incoming burst properly through the switch. This mechanism allows using state-of-the-art switching elements [5]. Other OBS solution is based on an end-to-end resource reservation protocol (also known as two-way reservation signalling) where the source node launches the burst in the network only after having received the acknowledgement from the destination node. This solution is less interesting for long-haul network applications due to the large latency and is not addressed in this paper.

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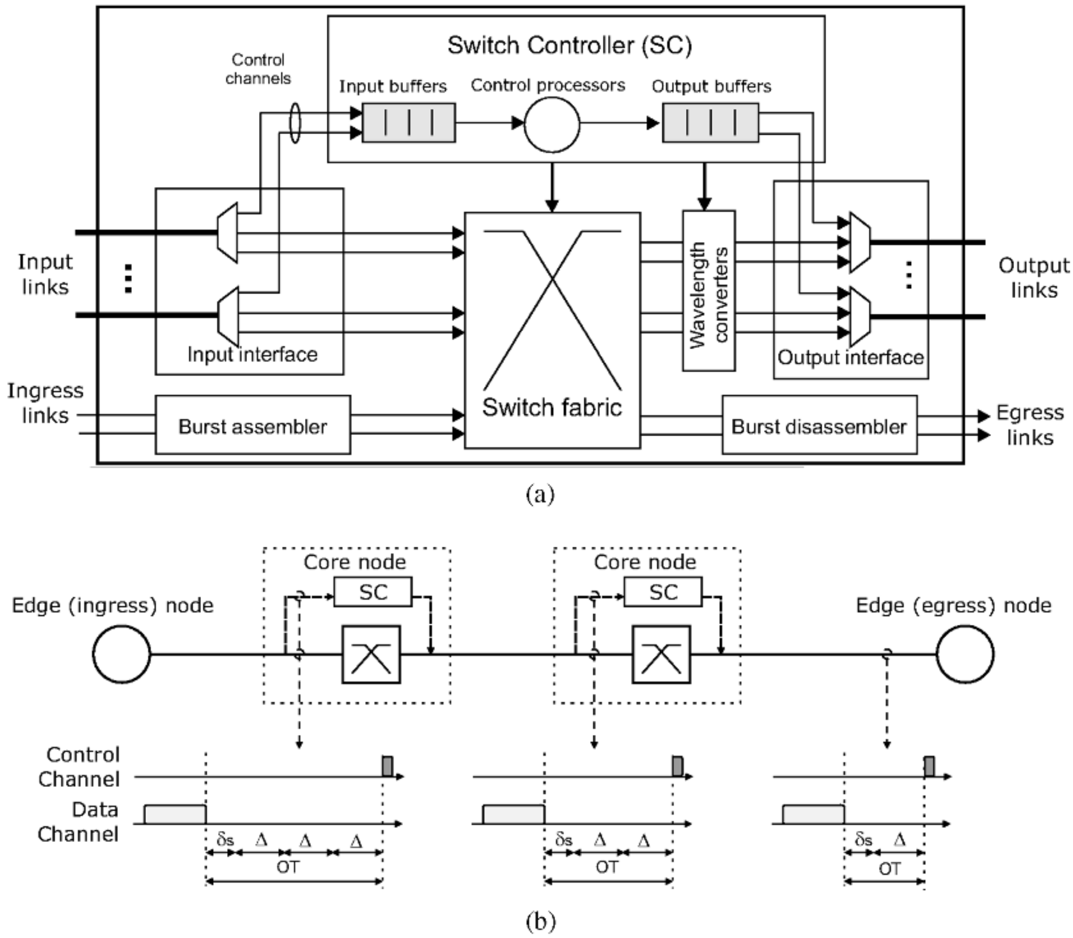


Fig. 1. (a) General C-OBS node architecture and (b) an example of behavior. Δ is the 1-hop offset time corresponding to the queuing and processing delay of one node, δ_s is the switching delay, and OT is the global offset time.

It is clear therefore that the offset time is a crucial parameter in OBS networks and the literature proposes two solutions for its provisioning.

In the source-based [1] architecture, referred hereafter as *conventional OBS* (C-OBS), the offset is setup once at the edge node in a soft way, through the delay of the burst transmission with respect to the BCP. At each core node, the offset time decreases by the time the BCP spends in the switch controller. This solution is the one most adopted in the research community.

In the distributed [6] architecture, referred hereafter as *offset time emulated* OBS (E-OBS) [7], the edge node sends the BCP and the burst together. The offset is introduced at each core node in a hard way by means of additional fiber delay unit, which postpones the arrival of the burst to the switch.

In this paper, we claim that the distributed offset time provisioning of E-OBS is appropriate for any scenario, whilst C-OBS may present some shortcomings such as difficulties to allocate fairly the shared resources. A particular gain of E-OBS is the reduced control complexity, both at the BCP processing and the routing management, with the performance preserved at the same time. To extend our study to both network performance and quality of service (QoS) context, we also address the problem of burst preemption applied in E-OBS. This part of our work is justified by unwanted preemption overhead produced in C-OBS.

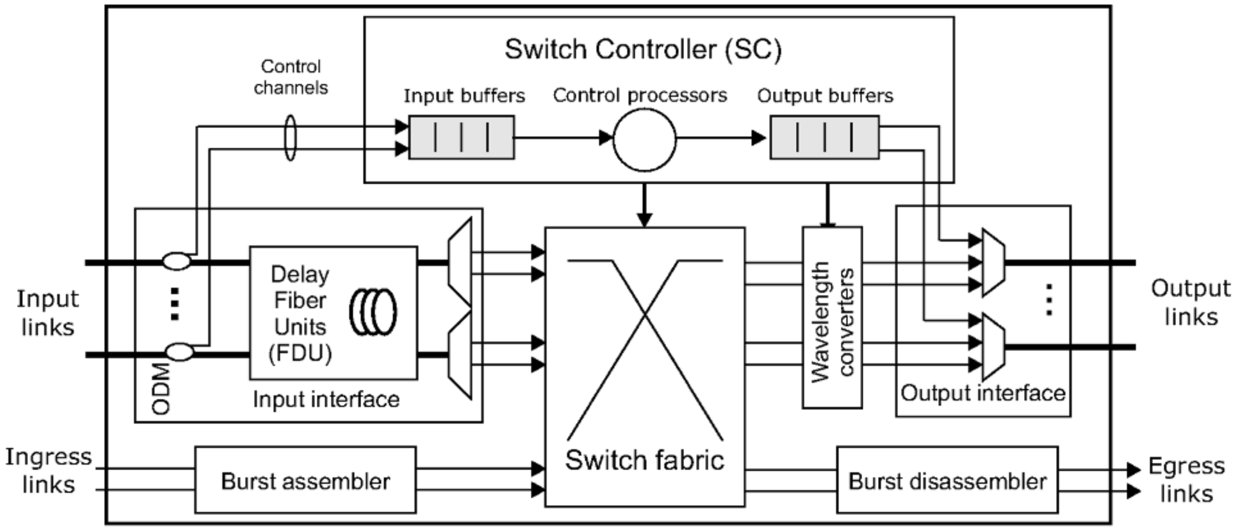
Last but not least, it is worth to mention that distributed offset time provisioning has attracted very little attention in the past. Through the discussion we undertake in this paper we would like to fill this gap.

The rest of the paper is organized as follows. Section II details the differences between the C-OBS and E-OBS architectures. Section III presents the rationale for E-OBS; particularly, it demonstrates that C-OBS possesses many drawbacks that can be easily avoided in E-OBS. Some of the discussed issues are the problem of unfairness in resource reservation, difficulty with alternative and backup routing, efficiency and complexity of burst scheduling, and facilities in QoS provisioning. In Section IV we propose a preemption window mechanism that expands look-ahead processing window techniques to the burst preemption in the E-OBS context. Section V concludes the paper.

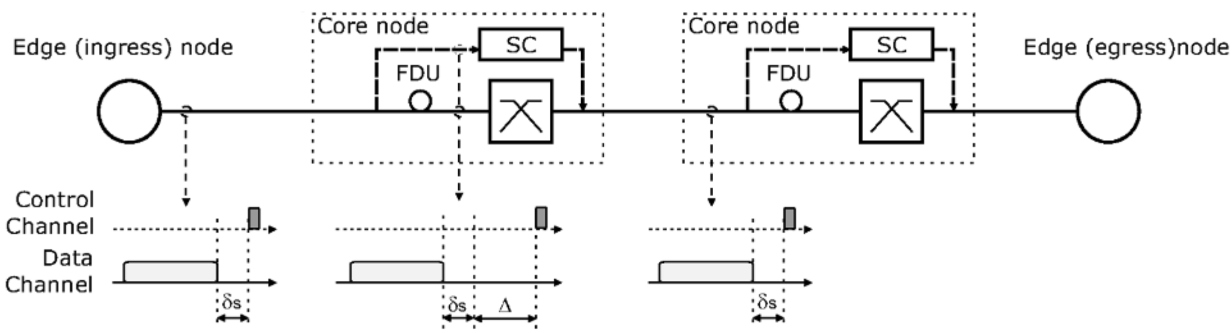
II. E-OBS Architecture

Figs. 1 and 2 highlight the difference between E-OBS and C-OBS architectures.

In a C-OBS network (see Fig. 1), the BCP is sent from the edge node prior to its burst with some pre-transmission offset time. This period is setup in order to provide enough time for processing the control information as well as for configuring in advance the optical switch matrixes in intermediate nodes along the transmission path. When the offset time expires, the



(a)



(b)

Fig. 2. (a) General E-OBS node architecture and (b) an example of behavior. ODM is the optical drop multiplexer, Δ is the 1-hop offset time corresponding to the queuing and processing delay of one node, and δ_s is the switching delay.

burst is released from the edge node and it goes through the just configured nodes whole the way remaining in the optical domain. At each node, the offset time decreases by the time BCP spends in the switch controller. The offset time is setup only once, in the edge node, and it is a global offset time which is supposed to compensate the switching and processing times at all the nodes lying on a routing path.

In an E-OBS network (Fig. 2), the node is a typical OBS node [6] with additional optical drop multiplexers (ODMs) to extract the control channels and a pool of fiber delay units (FDUs) introduced into the data path of the input interface—each input fiber is connected to one FDU. The E-OBS architecture allows a different control operation than C-OBS. The edge node launches the BCP into the control channel prior to its data burst and with some small offset time provided to compensate the switch reconfiguration delay at the egress node. At each core node, while the data burst is delayed by the FDU, the BCP goes directly to the switch controller. During the time the burst is held in the FDU, the BCP undergoes the queueing in an input buffer and the processing in one (or more) control processor(s). Before being converted back to optical form and transmitted through the output control channel to the output interface, the BCP is buffered in such a way that the offset time is renewed as it was at the ingress. This operation is repeated at each core node so that the offset time is kept fixed from link to link inside the network. Once the burst reaches the egress node, it is disassembled and the data are delivered to the client networks.

In a slightly different approach, the BCP can be released immediately after its processing without the output buffering phase. In such a case, the offset time increases hop-by-hop and the solution will present the same flaws as C-OBS. Thus, we prefer to maintain the offset time fixed even though it entails additional constraints on the control operation. In fact, events such as congestions in switch controller, variations of the propagation delay due to physical impairments, contentions of BCPs in control channel, etc. may cause insufficient offset time provisioning. In [8], we have addressed such a problem and shown that, in scenarios like the ones considered in this papers, bursts longer than some tens of kilobytes and delay budgets greater than 20 μs are enough to neglect it. Moreover, it has to be underlined that BCPs are sent at the edge nodes before the bursts with a switching time margin. Since BCPs are regenerated at each node, this margin could be retimed as well as adjusted to take into account any possible offset time variation.

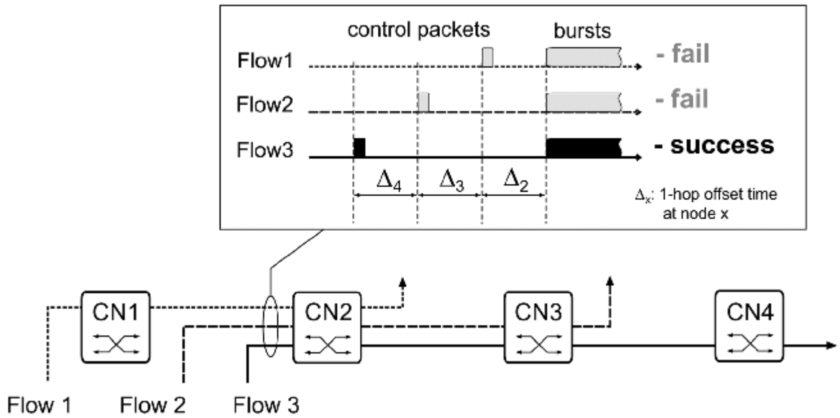


Fig. 3. Unfairness and path priority effect.

This E-OBS node architecture is very similar to the one commonly considered for optical packet switching (OPS) (see for example [9]), what eventually may promote further E-OBS migrations toward real OPS. It has to be stressed out, however, that there are still some fundamental differences between E-OBS and OPS such as, e.g., the out-of-band control, the size of data carrier (burst/packet), the use of bufferless nodes, as well as the asynchronous mode of operation that is not very common in OPS (see for example [10]). Few OPS proposals adopt the OBS out-of-band transmission of control information (e.g., [11] and [12]) but they are mainly designed for metro networks and consider synchronous and slotted packets. Hence, both ideas should not be mixed-up, and, definitively, E-OBS is an optical network architecture somewhere between C-OBS and OPS.

Note that in the literature the FDU term is usually replaced by the fiber delay line (FDL) term; nevertheless, we emphasize the use of FDU so that to distinguish this component from more complex FDL buffers. The FDU is a piece of fiber of fixed and limited length and it does not require any switching capability. There is a need for only one FDU per each input port. Considering that the maximum nodal degree in frequently referenced mesh network topologies does not exceeds five [13], the introduction of a pool of FDUs into an OBS node should not cause much trouble. Moreover, two facts actually confirm the viability of the use of such components and, particularly, their application to the E-OBS architecture. On one hand, FDUs are commercially available (e.g., see [14]); exemplary parameters of these components are: insertion loss <0.3 db/km, fiber length up to 4 km what corresponds to 20 μs of delay, operating wavelengths $1260 \div 1650$ nm, dimension 6 in $\times$ 6 in $\times$ 1.59 in with enclosure. On the other hand, OBS demonstrators that operate with FDUs have been showcased recently (see for example [15]).

Finally, a highly advantageous role of the FDU is the regeneration of optical signal entering the node since this piece of fiber can act as a dispersion compensation unit. In [16], it is discussed that the dispersion of a typical 70-km-length amplification span is compensated by 12 km of dispersion-compensation fiber (DCF). In the context of E-OBS architecture, such a fiber could be built into the node input interface so that to realize two functions: optical compensation and offset time provisioning.

III. Performance Comparison

In this section, we prove that E-OBS solves easier than any other solution the problems encountered in the C-OBS architecture. As we will see, the counterbalance is the use of additional optical component, one per each input port of each core node.

A. Fairness

An inherent feature of C-OBS is the variation of offset times in the network. Indeed, while the burst goes through the network, the offset time decreases at each hop by the time BCP spends in the switch controller. As a result, bursts routed over different paths may have different offset times at a given node. This effect induces several difficulties which we discuss in details in this and next subsections.

It is well-known that a burst of higher number of residual hops to reach the destination—hence of higher offset time—has more chances to reserve an output wavelength than a burst of shorter offset time [17]. This path length priority effect results in higher loss probability of bursts that are approaching their destination [18]. As a matter of fact, such bursts can be easily overtaken by the bursts of higher offset times, e.g., which have just been released from the ingress node. As a consequence, this effect produces an unfairness in access to transmission resources among different burst flows and unnecessary waste of transmission resources reserved in all the upstream nodes traversed by the lost burst.

Several solutions have been proposed to mitigate this effect in past years (see, e.g., [19] and [20]). Most of them apply either preemptive or early discard technique to achieve a fair bandwidth allocation.

A preemption technique allows overwriting of some resources, previously booked by one or more preceding bursts, for a later arriving burst; the preempted bursts are discarded. The major problem of such technique is the creation of so-called *phantom bursts*, i.e., BCPs associated with the preempted bursts that continue their trip towards the destination and reserve resources at each downstream node on the routing path. Therefore, either an additional signaling procedure is required to release these reservations or the resources are wasted. In order to assess it, in [22] we derived an approximate model to estimate the preemption overhead that is produced in a node. It highlights that under moderate and high traffic load conditions or in a link of few number of wavelengths, a significant amount of resources is unusable due to the presence of phantom bursts. Additionally, phantom bursts increase unnecessarily the congestion in the control plane which may affect system stability and performance at high loads [8].

On the other hand, the application of any burst discarding technique involves a decrease in overall network performance and additional burst scheduling complexity. The latter is very important since it influences the dimensioning of key OBS parameters, such as burst lengths, offset time duration, the capacity of electronic memory installed at the edge nodes, etc. (see, e.g., [8] and [21]).

The most innovative solution is the one proposed in [23] (and extended in [24]) where the resource requests are separated from the scheduling. Two BCPs are therefore required: the first one advertises the arrival of a burst; the second one makes the reservation. Nonetheless, the double BCPs increase the amount of control information (at least it doubles the number of BCPs headers) and, consequently, the controller efforts. Moreover, it can produce control troubles if, for some processing errors, the BCPs are disordered.

In Fig. 4, we present some exemplary simulation results which evaluate fairness in C-OBS and E-OBS networks; C-OBS does not apply any fairness-improving technique. In the evaluation, we focus on the fairness goodness, i.e., the variation of burst loss probabilities with respect to the residual number of hops to reach the destination for different network topologies. For such a purpose, we define the coefficient f as a ratio of the mean burst duration and 1-hop offset time (i.e., the portion of time the BCP is supposed to spend in a switch controller). In particular, we fix the 1-hop offset time to 10 μs and vary the mean burst duration. For each topology, we select a network load (i.e., a given amount in Erlangs) so that the overall burst loss probability is in the range of 10^{-2}. Here, we report the results only for the 15-nodes ring and the NSFNet topology; the performance obtained with other topologies is similar to these ones. The details of the simulation scenario are presented in Appendix I. We stress only the fact that the C-OBS nodes apply the Just Enough Time (JET) resource reservation and Last Available Unscheduled Channel with Void-Filling (LAUC-VF) scheduling, while the E-OBS nodes operate with less complex Horizon and LAUC scheduling. The reasons are discussed in Section III-C.

We can see that the fairness in C-OBS is very poor. The bursts that begin their trip (i.e., of high number of residual hops, the right hand side of the figures) may undergo much lower losses than the bursts having just the ultimate hops to reach the destination. Fairness can be achieved only with very long bursts. In fact, the unfairness vanishes only if the burst duration is at least 200 times larger than the 1-hop offset time (higher f values); in our scenario, it corresponds to 2 ms of mean burst duration (or 2.5 MB of data burst at 10 Gbit/s).

On the contrary, the E-OBS resolves the problem of unfairness itself, thanks to its fixed offset time provisioning. In fact, in the E-OBS architecture each burst has the same time horizon to

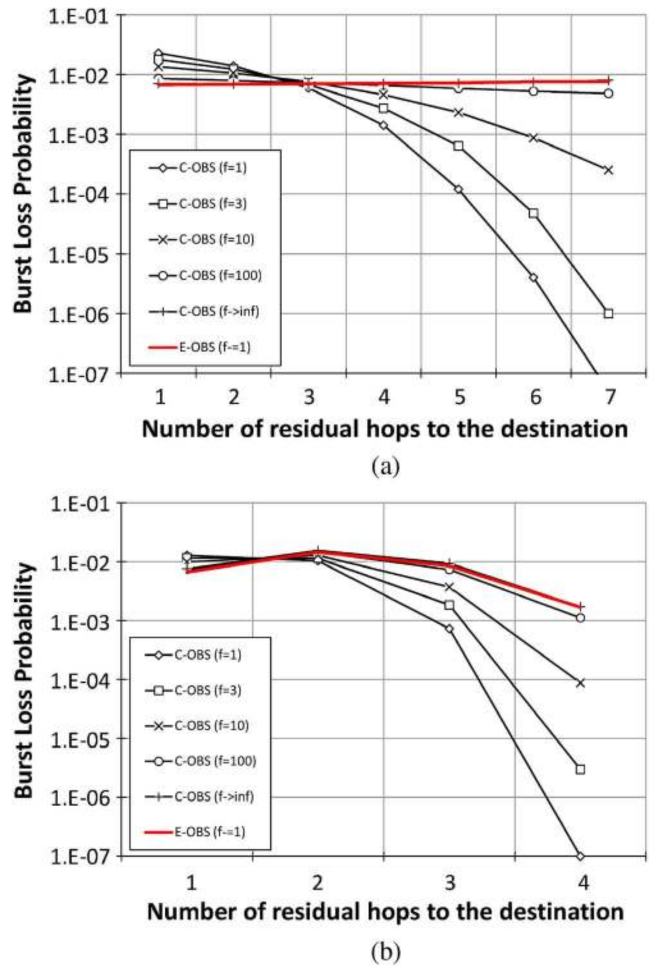


Fig. 4. Burst loss probability as a function of the residual hops number. (a) 15-nodes ring (loaded with 11.2 Erlangs), and (b) NSFNet (19.2 Erlangs). C-OBS uses JET/LAUC-VF scheduling while E-OBS uses Horizon/LAUC.

make the reservation of resources since the offset times, which are determined by the length of FDU, are the same. The results presented in the figure confirm this ability. In particular, we can observe that the burst loss probabilities are much more stabilized even for very short bursts and without regard to the network topology; the slight variation observed in the Fig. 4(b) is due to unbalanced load distribution of the shortest path routing in the irregular NSFNet topology.

In summary, the unfairness in access to transmission resources for bursts belonging to different flows disappears in E-OBS.

B. Burst Loss and Delay Performance

A possible consequence of achieving fairness could be the worsening of network performance. In this section, we show that both burst loss probability and delay performance are comparable or even better in E-OBS than in C-OBS.

On one hand, although the results presented in Fig. 4 might give an impression that the overall burst loss probability is higher in E-OBS than in C-OBS, still, it is not the case. This is reflected in Fig. 5(a), where we compare the overall burst loss probability as a function of offered traffic load. As we can see, the E-OBS architecture offers as good performance as C-OBS.

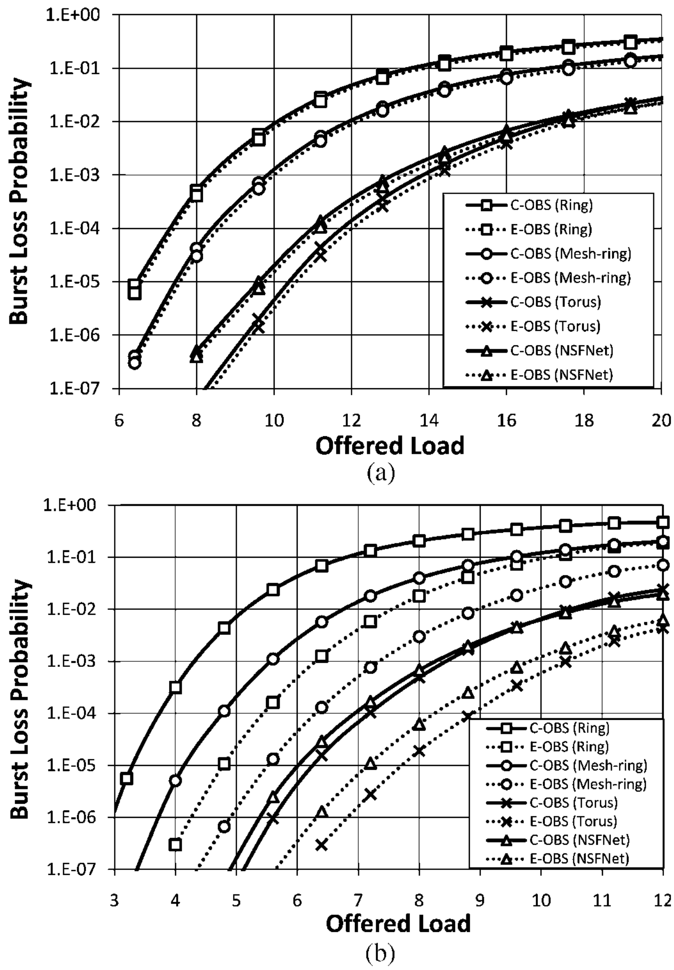


Fig. 5. Burst loss probability as a function of the offered traffic load comparing E-OBS and C-OBS under different topologies. (a) C-OBS uses JET/LAUC-VF scheduling while E-OBS uses Horizon/LAUC. (b) Both C-OBS and E-OBS use JIT/LAUC.

We recall that only C-OBS applies the more complex burst scheduling with void filling enhancement.

Two facts justify this result. First, as commented in Section III-A, in C-OBS it is more probable to discard a burst when it is close to the destination (few number of residual hops) and such a discarded burst has traveled throughout the network and occupied wavelength resources uselessly. Secondly, there are more bursts requiring few hops to reach their destination than those requiring many hops; in fact all bursts need at least one last hop to reach the destination, less bursts require two hops, even less bursts require three hops and so on. Consequently C-OBS discards the majority of bursts when they are close to the destination and this worsens the overall burst loss probability.

On the other hand, the average end-to-end delay $\overline{D}$ produced in OBS networks is due to the average burstification time $\overline{B}$, the link propagation delay d (approx. 1 ms in 200-km link) and the offset time provided for the 1-hop control processing Δ (up to some μs) and switching δ_s (below μs in "fast" switching, e.g., see [15] and [25]) purposes. We have already assumed that in E-OBS the switching time is introduced between the burst control packet and the data burst in the edge node. Hence, the delay $\overline{D}$ the burst undergoes is the same in both C-OBS and E-OBS architectures, and it can be expressed as

$$\overline{D} = \overline{B} + \sum_{i=1}^{n}(d_i + \Delta_i) + \delta_s$$

where n is the number of hops in the path.

This equivalence can be also observed when comparing Figs. 1 and 2. Note that the propagation time is still the dominant delay factor in both cases.

C. Resource Reservation

One of the main challenges of OBS is to schedule the bursts efficiently so that the throughput is maximized and the burst losses are minimized. Several resources reservation methods have been proposed in the literature (see, e.g., [6]). The just-in-time (JIT) resources reservation algorithm performs an immediate resource reservation as it checks the wavelength availability just at the moment of the BCP processing. On the contrary, both Horizon and JET perform a delayed resources reservation for the period beginning at the burst arrival time. The difference between these algorithms is that Horizon searches for a wavelength that does not have any later reservations while JET allows for filling the voids that occur between reservations.

As commented in [26], in C-OBS there is an tradeoff between complexity and performance: JIT and Horizon schedulers are preferable for their $O(1)$ runtime but present both high overhead and poor performance. On the contrary, void-based schedulers are highly efficient but present a $O(logm)$ complexity and require $10logm$ memory accesses to schedule a single burst (where m is the number of voids per wavelength).

To overcome the problem, the Constant Time Burst Resequencing (CTBR) scheduler was proposed in [26], which, by means of resequencing the BCPs, is able to avoid voids between bursts. In this way, the simple Horizon scheduler performs as efficiently as the void filling one. Nonetheless, this solution is prone to create phantom bursts.

E-OBS can operate with any resources reservation algorithm. Offset times in E-OBS are fixed and much smaller than in C-OBS so the effect of the resources over-provisioning due to early reservations of JIT has lower impact on the performance. To emphasize this merit, we report in Fig. 5(b) the comparison between E-OBS and C-OBS when both adopt the JIT algorithm. Moreover, E-OBS does not experience the offset time variation inside the network and, if we consider the nodes without FDL buffering, voids cannot be created between bursts and thus void filling enhancement is not necessary: JET and Horizon schedulers perform equally in E-OBS.

D. Routing and Survivability

Another important issue is the routing management. In C-OBS networks, the edge nodes should be aware of the routing path, yet before the BCP transmission, in order to calculate and setup the offset times accurately. If alternative (or deflection) routing is allowed inside the network, the problem of *insufficient offset time* may emerge. Indeed if an alternate route is longer than the primary route and, consequently, the

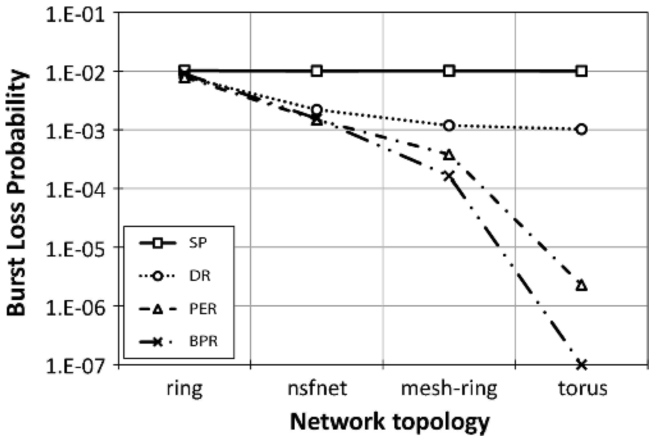


Fig. 6. Burst blocking probability as a function of the network nodal degree comparing SP and DR algorithms applied to C-OBS and PER and BPR algorithms applied to E-OBS in different network topologies; the benchmarking reference is the 10^{-2} performance of SP routing.

BCP does not have enough time to reserve resources ahead of the data burst, the burst is dropped. For this reason, either the offset time should be calculated for the worst case (i.e., for the longest possible alternative path) what may result in superfluous burst delay, or additional hardware (an output FDL like in [27]) or control mechanisms [28] have to be involved in order to diminish this effect. Moreover, several solutions that are oriented on network load balancing [31] and contention resolution by means of deflection routing [32] use preemption techniques, which again create phantom bursts in C-OBS networks.

For what regards survivability, some restoration mechanisms presented in the literature consider deflection routing to coop with link failures in C-OBS (e.g., [29], [30]). Again, an important factor that has to be taken into consideration here is the insufficient offset time problem. Therefore, the choice of the offset time is very critical due to its influence on the burst losses in C-OBS networks.

In E-OBS, the offset time is introduced in each core node thus the routing paths can be created freely inside the network with any alternative or load balancing routing algorithm and the insufficient offset time effect never occurs.

As an example, Fig. 6 compares four routing algorithms applied in different network topologies; the x-axis is ordered according to the nodal degree (respectively, 2 for ring, 2.93 for NSFNet, 3 for mesh-ring, and 4 for torus). In this analysis, a benchmarking reference for the burst loss probability, obtained with the Shortest Path (SP) algorithm in C-OBS, is defined at the level of 10^{-2}; this reference implies a load of 10.08, 16.86, 11.97, 17, 28 Erlangs for ring, NSFNet, mesh-ring, and torus topology, respectively. Under these load conditions, we evaluate the overall burst losses for the classical Deflection Routing (DR) algorithm applied to C-OBS, and two algorithms, namely Path Excluding Routing (PER) and Bypass Path Routing (BPR), applied to E-OBS.

Recall that DR is an hop-by-hop routing which allows to selecting an alternative output port in case of congestion at the output port of the shortest path; if the deflection succeeds, following nodes are in charge of redirecting the burst towards the destination. In this analysis, we consider that the DR algorithm is limited to paths with two more hops than SP at maximum.

Both BPR and PER algorithms, which were originally proposed for optical packet switching networks [35], perform a deflection of transmitted burst from a primary to an alternative routing path (three paths are preestablished between any pair of nodes) if there are no transmission resources available on the primary path (due to congestion or failure). The routing decision is taken per burst on the base of only local (isolated) output link state information. This implies that neither the algorithms require any knowledge about the network state nor any signalling state advertisement is necessary.

The results indicate that, in a ring topology, alternative routing algorithms do not bring any benefits. Increasing the nodal degree from 2 to 4, while DR presents slightly better performance than SP, the gain of PER and BPR becomes significant (DR suffers indeed the insufficient offset time problem). Between them, BPR achieves the lowest burst losses.

E. QoS Provisioning

Several methods have been considered in the literature to support QoS provisioning in OBS networks. Among them the offset time differentiation and the burst preemption can offer the utmost performance with regard to the class differentiation [33]. The former assigns an extra offset time to high priority bursts in order to favor them while the resources reservation mechanism is performed. In case there are no available resources, the latter allows to reassigning some resources previously reserved for low priority bursts to high priority bursts.

It was proven that the performance of the offset time differentiation mechanism may be affected by the multiplication of effective classes due to the offset variation [17]. In order to diminish this effect the extra offset times should be high enough in C-OBS (at least some times the offest time). E-OBS does not have such limitations due to its fixed offset time provisioning.

Burst preemption-based mechanisms, as already commented, create phantom bursts in C-OBS. In Section IV we show that the problem of phantom burst can be effectively avoided in E-OBS applying a look-ahead processing window technique.

F. Hardware Complexity

An issue of some importance regards the amount of space required to store the assembled bursts in electronic buffers of the edge nodes during the entire offset time period. The buffer capacity greatly depends on the burst assembly parameters as well as on the offset times. In some OBS scenarios the burst payloads are considered to carry some megabytes of data and, in case of slow core node processors, the offset times can be very large. As a result, the memory requirements in C-OBS can be high.

In E-OBS the burst, after its assembly, has to wait in the edge node only for a short period corresponding to the switching delay δ_s. Then it is sent towards the network as soon as there are free transmission resources in the output link of the edge node.

There is some additional hardware complexity in E-OBS due to the need for ODMs and FDUs that have to be introduced at the input ports of core nodes (we have already discussed this issue

TABLE I
SUMMARIZED COMPARISON BETWEEN C-OBS AND E-OBS

Feature	C-OBS	E-OBS
Fairness	No	Yes
Performance	BLP better in E-OBS; same e2e delay	
Scheduling complexity	High, VF required	Low/medium
QoS provisioning	Difficulties	Facilities
Routing adaptability	Limited	Not limited
Additional hardware	RAM at the edge	FDU+ODM in core

in Section II). Typical FDU delays necessary for E-OBS operation range from some μs to tens of μs, depending on switching and control processing technologies (e.g., see [34]) as well as particular choices for control algorithms (resources reservation, scheduling, etc.) and QoS provisioning (see Section IV). Therefore, we consider the lengths of FDU to be between $2 \div 8$ km.

The attenuation of optical signal (below 0.3 dB/km) should be taken into account when analyzing the power budget and designing the amplification stages. It is important to say that there is a need for only one FDU per node input port; such FDU will compensate offset times for all the data channels simultaneously. The control channel should be extracted before and brought to the switch controller.

G. Summary

Table I summarizes both the drawbacks and qualities of the discussed offset time provisioning architectures. The E-OBS surpasses the C-OBS in many aspects; hence, there is a motivation for recognizing the E-OBS architecture as an efficient and functional solution for OBS networks. We recall that BLP: Burst Loss Probability, VF: Void Filling, RAM: Random Access Memory, FDU: Fiber Delay Unit, ODM: Optical Drop Multiplexer.

IV. QoS Preemption Window Mechanism

A. Principle of Operation

Several strategies have been considered to provide contention resolution with QoS provisioning in OBS networks. The most effective solution is the burst preemption [33]. A burst preemption mechanism allows the switch controller to overwrite a Low Priority (LP) reservation with a later arriving High Priority (HP) one if no more resources are available. Preemption concerns either an entire burst reservation (*full preemption*) or it allows for a partial preemption if a *burst segmentation* technique is applied. As commented in Section III-A, the general drawback of preemption techniques is the generation of phantom bursts.

To eliminate this effect, in [39] we proposed the Preemption Window (PW) mechanism, which expands look-ahead processing window techniques to the burst preemption context [38]. In this paper, we show that the E-OBS architecture facilitates the support to the PW mechanism. Indeed, a BCP can be delivered to the switch controller with some extra period besides the 1-hop offset time Δ. This additional time constitutes the preemptive window T during which the controller can preempt low priority reservations by the one of higher priority. As in E-OBS, the BCP remains in the switch controller until the entire offset time $T+\Delta$ expires and only then it can be sent to the next node together with the burst (if it has not been preempted) or dropped (in case of successful preemption). An important rule of the PW mechanism is that, once the BCP is sent, the preemption of the burst is not allowed in the node.

Fig. 7 shows an illustrative example of the PW mechanism. In this example, a preemption of the LP burst 1 can be performed only by the HP burst 2 since the BCP of the latter arrives in preemptive window T. On the other hand, the HP burst 3 is not allowed to preempt the LP burst 1 because its BCP arrives out of window T. It has to be noted that the preemption window T begins after the end of the offset time of the BCP (Δ) and lasts until its transmission. The sum of T and Δ represents the delay that the FDU must introduce at each core node. At the output port, the BCP and the successfully switched burst are then sent together. For simplicity and clearness, the switching time δ_s is not depicted in these figures.

Thanks to these rules. any BCP coexists with its data burst and no phantom bursts are created. Therefore, there is no need for any signaling procedure to be carried out in order to release the resources on the outgoing path in case of successful burst preemption. It should be pointed out that the PW mechanism can work with both full and partial burst preemption techniques.

Theoretically, it is possible to apply the PW mechanism also in the C-OBS architecture. In such a case, edge nodes should introduce an additional offset time to comprise the preemption windows for all possible nodes on the routing path. A disadvantage of this solution is the increase of offset time variation, which intensifies the effects discussed in Section III-A. For this reason we consider the PW mechanism more appropriate for E-OBS.

The value of T becomes an important tradeoff between long FDUs (too large PW) and ineffective burst preemption (too short PW). Scope of the following sections is to determine the minimum value of T that provides optimum performance in case of single (Section IV-B) and multi-wavelength (Section IV-C) node scenarios. Once T is determined, we complete the analysis considering a network scenario (Section IV-D).

B. Analytical Model

In this section, we analyze the burst loss probability of the high priority (HP) and the low priority (LP) class, in a single channel system where a full burst preemption mechanism and PW principle is applied. We assume Poisson processes for both the HP and LP burst arrivals with rates λ_{HP} and λ_{LP}, respectively. The total arrival rate to the node will be $\lambda = \lambda_{\text{HP}} + \lambda_{\text{LP}}$. Let us denote the i.i.d. exponentially distributed random variables for the burst inter-arrival times as t_{HP} and t_{LP}, respectively, for HP and LP class. Also, let l denote the burst duration, which follows an exponential distribution with mean value $1/\mu$; we assume the same service distribution for both classes.

Given a Markov chain identifying the three possible wavelength states, namely Q_0 for free wavelength, Q_{LP} if occupied

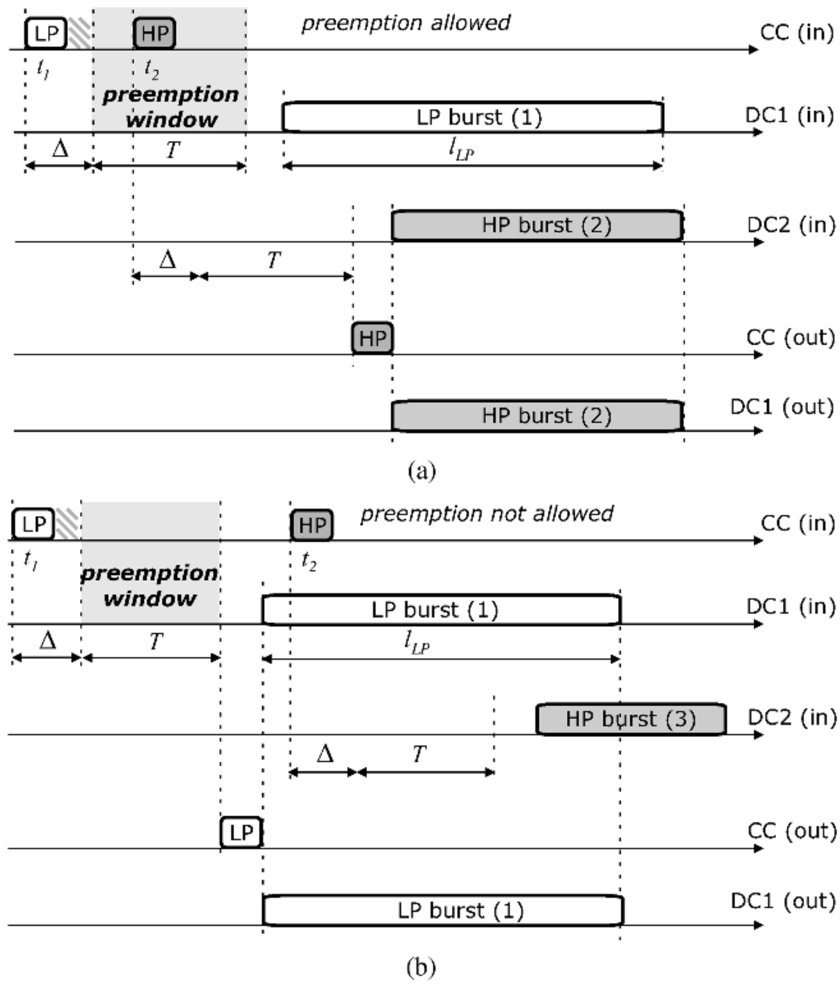


Fig. 7. Principle of the preemption window mechanism, (a) successful preemption, and (b) preemption not allowed due to the expiration of T. Δ is the 1-hop offset time, T is the preemption window, t_n is the BCP arrival time, l is the length of the burst, CC is the Control Channel, and DC is the Data Channel. The switching time is removed for simpleness.

by an LP burst, and $Q_{\rm HP}$ if occupied by an HP burst, we can easily determine the steady state probabilities

$$\begin{aligned} Q_0 &= \frac{\mu}{\lambda+\mu} \\ Q_{\rm LP} &= \frac{\lambda_{\rm LP}\mu}{(\mu+p\lambda_{\rm HP})(\lambda+\mu)} \\ Q_{\rm HP} &= \frac{\lambda_{\rm HP}(\mu+p\lambda)}{(\mu+p\lambda_{\rm HP})(\lambda+\mu)} \end{aligned} \tag{1}$$

and burst loss probability of LP and HP bursts

$$\begin{aligned} B_{\rm LP} &= Q_{\rm LP} + Q_{\rm HP} + p\frac{\lambda_{\rm HP}}{\lambda_{\rm LP}}Q_{\rm LP}, \\ B_{\rm HP} &= Q_{\rm HP} + (1-p)Q_{\rm LP} \end{aligned} \tag{2}$$

where p is the probability of a successful preemption (referred as $P(Y)$) with respect to all attempts of preemption (referred as $P(A)$).

Fig. 7 helps to discriminate successful and failed preemption. For sake of simplicity, we neglect the length of BCPs and assume $\Delta = 0$. In such a case, the arrival times of BCP and burst differ by the constant T and consequently the interarrival times between two BCPs and two bursts have the same statistics. Therefore, preemption happens if BCP of the HP burst $(t_{\rm HP})$ arrives before the preemption window T expires, which implies $t_{\rm HP} < T$, and preemption is needed if the HP burst $(t_{\rm HP} + T)$ arrives before the end of the LP burst $(l_{\rm LP} + T)$, which implies $t_{\rm HP} < l_{\rm LP}$ after simplification. Therefore, the probability of successful preemption $P(Y)$ can be calculated as

$$\begin{aligned} P(Y) &= P\left((t_{\rm HP} < T) \cap (t_{\rm HP} < l_{\rm LP})\right) \\ &= \int_0^T \int_y^\infty \mu e^{-\mu x}\lambda_{\rm HP} e^{-\lambda_{\rm HP} y}\,dx\,dy \\ &= \frac{\lambda_{\rm HP}}{\lambda_{\rm HP}+\mu}\left(1 - e^{-(\mu+\lambda_{\rm HP})T}\right). \end{aligned} \tag{3}$$

The probability $P(A)$ is

$$\begin{aligned} P(A) = P(t_{\rm HP} < l_{\rm LP}) + P\left((t_{\rm HP} < l_{\rm LP}) \cap (t_{\rm HP} > T)\right) \\ \times \sum_{i=1}^{\infty} P(t_{\rm HP} < l_{\rm LP})^i \end{aligned} \tag{4}$$

which represents the first HP burst arrival when the wavelength is occupied by an LP burst $(t_{\rm HP} < l_{\rm LP})$ and all further HP

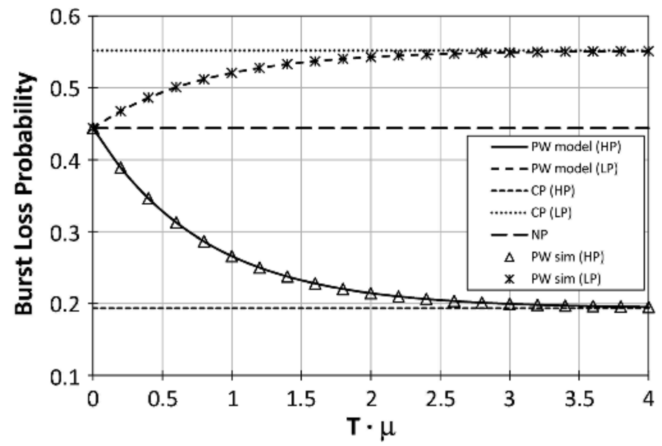


Fig. 8. Simulation versus modeling results ($\lambda = 0.8$, 30% of HP traffic, $\mu = 1$).

arrivals (the summation) in case of the preemption fail ($t_{\mathrm{HP}} < l_{\mathrm{LP}}$ and $t_{\mathrm{HP}} > T$). Solving (4) we obtain

$$P(A) = \frac{\lambda_{\mathrm{HP}}}{\mu+\lambda_{\mathrm{HP}}} + \frac{\lambda_{\mathrm{HP}}}{\mu+\lambda_{\mathrm{HP}}} e^{-(\mu+\lambda_{\mathrm{HP}})T} \sum_{i=1}^{\infty} \left(\frac{\lambda_{\mathrm{HP}}}{\mu+\lambda_{\mathrm{HP}}}\right)^i = \frac{\lambda_{\mathrm{HP}}}{\mu+\lambda_{\mathrm{HP}}} \left(1 + \frac{\lambda_{\mathrm{HP}}}{\mu} e^{-(\mu+\lambda_{\mathrm{HP}})T}\right). \quad (5)$$

The probability of successful preemption p is therefore

$$p = \frac{P(Y)}{P(A)} = \frac{1 - e^{-(\mu+\lambda_{\mathrm{HP}})T}}{1 + \frac{\lambda_{\mathrm{HP}}}{\mu} e^{-(\mu+\lambda_{\mathrm{HP}})T}}. \quad (6)$$

Taking into account (2) and (6) we have

$$B_{\mathrm{LP}} = \frac{\lambda}{\lambda+\mu} + \frac{\lambda_{\mathrm{HP}}\mu\left(1 - e^{-(\lambda_{\mathrm{HP}}+\mu)T}\right)}{(\lambda_{\mathrm{HP}}+\mu)(\lambda+\mu)},$$
$$B_{\mathrm{HP}} = \frac{\lambda}{\lambda+\mu} - \frac{\lambda_{\mathrm{LP}}\mu\left(1 - e^{-(\lambda_{\mathrm{HP}}+\mu)T}\right)}{(\lambda_{\mathrm{HP}}+\mu)(\lambda+\mu)}. \quad (7)$$

Two boundary conditions can be inferred from this model. If $T \to \infty$ in (7), the PW mechanism behaves as a classical preemption (CP) mechanism and an HP burst can always preempt an LP burst. If $T = 0$, there is no possibility of preemption (NP) and the mechanism operates as a simple scheduling without QoS differentiation. See the corresponding limits as follows:

$$\lim_{T\to\infty} B_{\mathrm{LP}} = \frac{\lambda}{\lambda+\mu} + \frac{\lambda_{\mathrm{HP}}\mu}{(\lambda_{\mathrm{HP}}+\mu)(\lambda+\mu)}$$
$$\lim_{T\to\infty} B_{\mathrm{HP}} = \frac{\lambda_{\mathrm{HP}}}{\lambda_{\mathrm{HP}}+\mu}$$
$$\lim_{T\to 0} B_{\mathrm{LP}} = \lim_{T\to 0} B_{\mathrm{LP}} = \frac{\lambda}{\lambda+\mu}. \quad (8)$$

In Fig. 8, we can see the discussed properties of the derived PW model; the results are validated by simulation (*PW sim*) results. We can see that for T between $3 \div 4$ of the mean burst duration $(1/\mu)$, the HP burst loss probability stabilizes and it approaches quickly its asymptote, which corresponds to the CP case.

Although the derived model concerns a single-wavelength scenario only, still, it allows to gain insight in the PW mechanism behavior. To complete the study and find feasible values of T, in the next section we provide simulation results of the PW mechanism in a multi-wavelength scenario.

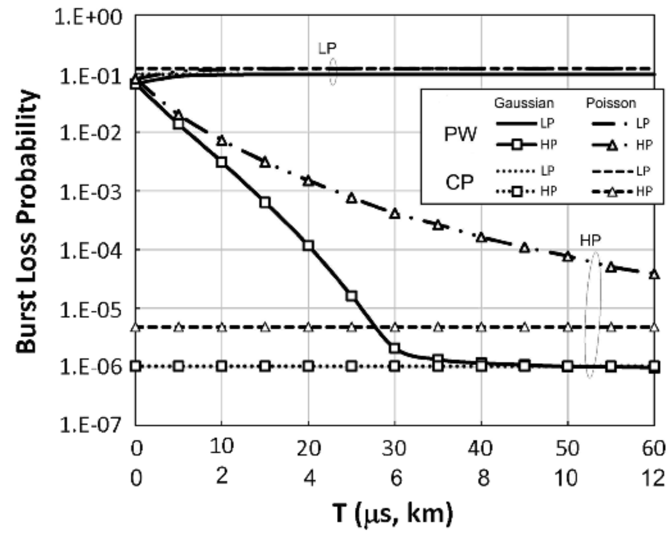


Fig. 9. Burst loss probability as a function of T comparing Gaussian and Poisson traffic models ($\alpha = 25\%$, $W = 16$, $\rho = 0.8$).

C. Node Simulation Results

In this evaluation, we consider a single E-OBS core node with 4×4 input/output ports. Beside the general Poisson traffic model we also consider a model with specific Gaussian burst length and inter-arrival time distributions which corresponds to the traffic generated by a mixed time-length burstifier [40]. A variance of 5 μs, and average, minimum and maximum burst length of 40 kB, 4 kB, and 4 MB are assumed, respectively. The HP traffic ratio over overall traffic is denoted as α. We define ρ to be the normalized load which expresses relative occupancy of each wavelength.

In Fig. 9, we first compare the Classical Preemption (CP) with our Preemption Window (PW) mechanisms as a function of the window T. When $T = 0$, PW is not able to discriminate between priorities and there is no possibility of preemption. If T increases, the HP (LP) burst loss probability decreases (increases) and approaches an asymptote, which corresponds to the performance obtained with CP. In case of Gaussian traffic, PW reaches quickly the CP performance (T larger than 30 μs), while with Poisson traffic the slope of the HP performance curve is smoother (T larger than 60 μs). The Gaussian traffic model allows to obtaining better results because it generates bursts with less variable durations, which match better with the length of the FDUs.

As Fig. 10 shows, burst loss probability would be further reduced in the systems with more wavelengths. Only Gaussian traffic model is considered in this study. We can see that for $T \geq 30$ μs (6 km) and $W \geq 16$ wavelengths, HP burst loss probability is less than 10^{-6}. It is also important to notice that the performance curves approach the asymptote of the CP scheme at the same length of the FDU; this fact facilitates the design.

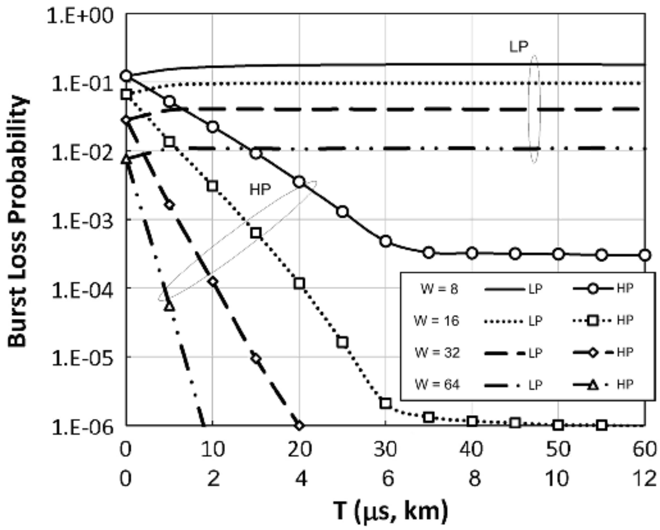


Fig. 10. Burst loss probability as a function of T and W ($\alpha = 25\%, \rho = 0.8$, Gaussian traffic model).

D. Network Simulation Results

In this section, we compare the classical preemption (CP) applied to the C-OBS architecture and the Preemption Window (PW) applied to the E-OBS architecture.

We consider only the Gaussian traffic scenario described above while the rest of the configuration parameters are detailed in Appendix I. The value of T is set to 8 km (40 μs) which corresponds to 1.25 times the average burst duration.

In Fig. 11, the comparison is in terms of BLP considering torus and NSFNet topologies. We select few number of wavelengths ($W = 8$ and $W = 16$) in order to have significant results for HP traffic. Although the considered topologies are very different, Fig. 11(a) and (b) present similar behavior. The results show that PW presents slightly better performance for LP traffic than CP. This improvement is mainly due to the absence of phantom bursts, which, as commented in Section IV-A, is a design feature of the PW mechanism. In terms of HP traffic, the two solutions provide close results.

In Fig. 12, we show another feature of the E-OBS architecture, and, consequently, of the PW mechanism in terms of class isolation. In this figure, we extend the study of fairness presented in Section III-A to the context of QoS provisioning. The EON topology is considered. We can see that the fairness in C-OBS for both LP and HP bursts is very poor. In fact, the bursts that begin their trip present much lower losses than the bursts having few hops to reach the destination. On the other hand, the E-OBS architecture confirm its ability to maintain stable performance independently of the number of residual hops to destination also when the PW technique is applied.

V. CONCLUSION

In this paper, we highlighted the advantageous of the offset time E-OBS in comparison to the C-OBS. We showed that C-OBS posses several drawbacks such as the problem of unfairness in access to transmission resources, constraints in the alternative routing, a need for complex void filling-based resource reservation algorithms, some difficulties in QoS provisioning, among other issues. On the contrary, the E-OBS can bring significant facilities to the mentioned problems at

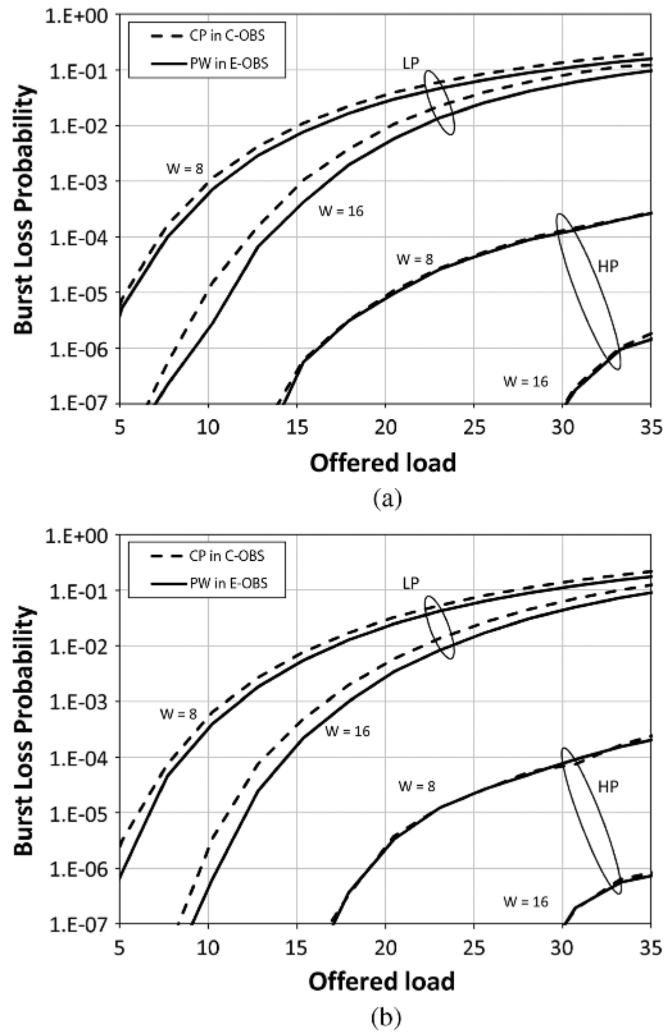


Fig. 11. Burst loss probability for LP and HP traffic comparing Classical Preemption (CP) and Preemption Window (PW) mechanisms in (a) torus topology and (b) NSFNet topology.

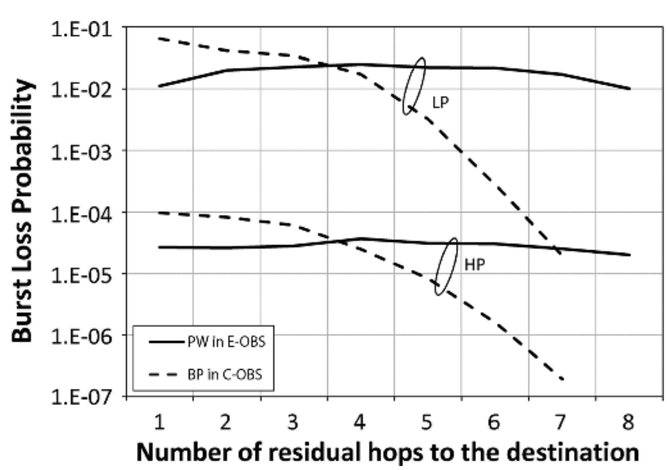


Fig. 12. Burst loss probability as a function of the number of residual hops considering the EON topology.

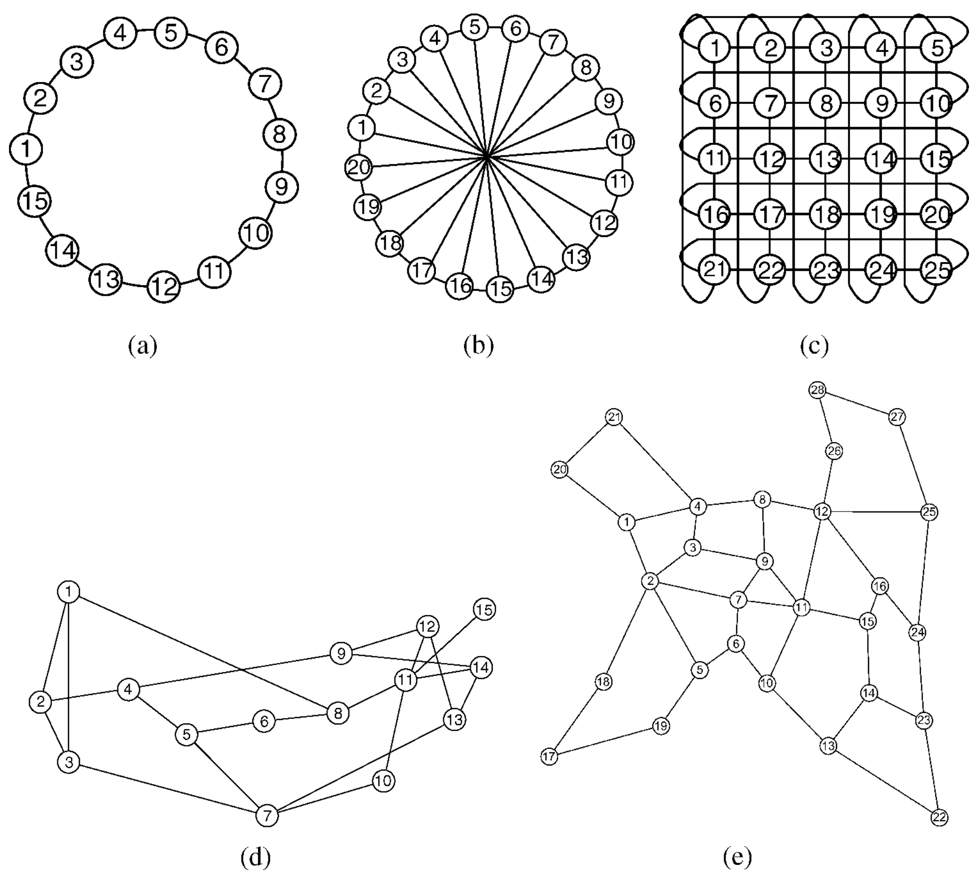


Fig. 13. (a) 15-nodes ring, (b) 20-nodes mesh-ring, (c) 25-nodes torus, (d) NSFNet, and (e) EON topologies.

the expanse of adding one FDU of few kilometers length per input port in the core nodes. Some quantitative and qualitative results show that E-OBS performs as well as C-OBS in terms of burst loss probability and end-to-end delay while using simpler resource reservation algorithm.

Moreover, we proposed the PW mechanism that allows the application of the burst preemption to provide QoS differentiation. Thanks to PW, there is no need of any additional protocols to avoid the generation of phantom bursts. We showed that, by increasing of few kilometers the length of the FDUs, PW achieves the same high-priority performance as the classical burst preemption scheme. At the same time, the absence of phantom bursts reduces the overall network load leaving more room to transmit low priority traffic. As a consequence, the PW mechanism when applied in E-OBS surpasses the overall performance of the classical burst preemption mechanism.

Taking into account all the arguments provided in this paper, the key message is that there is a motivation for recognizing the E-OBS network architecture as an efficient and functional alternative to C-OBS one.

APPENDIX I
SIMULATION SCENARIO

In our simulation scenario, we consider several topologies (see Fig. 13), three based on regular topologies: a 15-nodes ring network (with a nodal degree of 2), a 20-nodes mesh-ring network (3), and a 25-nodes torus network (4); and two real topologies: the NSFNet topology of 15 nodes and 22 links (with a nodal degree of 2.93), which represents an America backbone network, and the European Optical Network (EON) topology with 28 nodes and 39 links (2.78).

Network links are dimensioned with the same number of wavelengths $W = 32$. The transmission bitrate is 10 Gbps.

We assume each node is both an edge and a core bufferless node capable of generating bursts destined to any other nodes. A one-way signaling protocol, the JET resources reservation, and the LAUC-VF scheduling is applied to C-OBS networks. E-OBS uses a one-way signaling protocol as well but it is accompanied by the simpler Horizon and LAUC mechanisms. The switching and processing times are 1 μs and 10 μs, respectively.

The traffic is uniformly distributed between nodes. We assume each edge node offers the same amount of traffic to the network; this offered traffic is normalized to the transmission bitrate and expressed in Erlangs. In our context, an Erlang corresponds to the amount of traffic that occupies an entire wavelength, e.g., 51.2 Erlangs mean that each edge node generates 512 Gbps.

The bursts are generated according to a Poisson arrival process and have exponentially distributed lengths. If not differently mentioned, the mean duration of the burst is 32 μs (40 kB).

It is worth to mention that all simulation results have 99% level of confidence. It is achieved by means of at least ten repetitions of the same simulation.

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