Performance Evaluation and Design of Polymorphous OBS Networks With Guaranteed TDM Services

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***Abstract*—In Polymorphous Optical Burst-Switched (POBS) networks, the Burst Control Packets (BCPs) of conventional Just-Enough-Time based signalling OBS networks are given extended properties which enable them not only to reserve fixed time-slots for asynchronous data bursts, but also to allocate TDM reservations for periodic streams of data, and even a complete wavelength for high-bandwidth demanding services. This allows POBS to provide a flexible, yet transparent, approach for supporting the idiosyncrasies of today's most popular services over the same underlying network architecture. In POBS, the spare gaps in between synchronous TDM reservations can be used for the allocation of best-effort data bursts, leading to a more efficient utilisation of the optical capacity.**

This work shows how to extend the well-known Erlang Fixed Point procedure to evaluate the performance behavior of POBS networks, whereby asynchronous data bursts coexist with high-priority periodic TDM reservations. The performance evaluation algorithm is applied to a number of case scenarios, showing the benefits arisen due to the flexibility of POBS networks.

***Index Terms*—Erlang fixed point, IP television, polymorphous optical burst switching, sub-wavelength TDM reservations.**

I. Introduction

THE huge amount of bandwidth capacity provided by Dense Wavelength Division Multiplexed (DWDM) optical fibres, in the order of Terabits/sec [1], [2], suggests that optical switching is the only feasible solution to satisfy the ever-increasing demand of network capacity, which is estimated to double every year [3]. However, the appropriate management of such raw capacity still remains a subject of study since the electronic conversion of optical packets (O/E conversion) comprises a bottleneck for data transmission over optical networks.

In this light, three different paradigms have been proposed to carry IP traffic over WDM: Optical Packet Switching (OPS), Optical Burst Switching (OBS) and Optical Circuit Switching (OCS). While the former needs flexible optical buffering for the processing of packet headers, the latter requires the reservation of a complete wavelength per stream of packets which leads to the under-utilisation of network resources, and a further waste of such high bandwidth capacity. At present, only the Optical Burst Switching paradigm brings a high degree of bandwidth utilisation at a moderate complexity cost [4], [5].

In OBS networks, border nodes aggregate IP packets together into large-size data bursts, which are further switched by the core nodes all optically, that is, without any O/E/O conversion [6], [7]. Given the bufferless nature of OBS networks, a one-way reservation signalling protocol has been proposed to improve the performance of OBS networks: Just-Enough Time (JET) [4]. In JET, for each data burst, a Burst Control Packet (BCP) is generated and transmitted before its associated data burst. Such BCP is transmitted over a separated control channel, and suffers O/E and E/O conversion at each OBS node. The BCP contains the size and expected arrival time of its associated data burst, information which is used by the core nodes to allocate a time-slot for the forthcoming data burst. This strategy is shown to significantly reduce burst contention, however at the expense of increasing the end-to-end delay experienced by packets. Essentially, the time-difference between the BCP and its associated data burst must be large enough to properly schedule a change of state in the optical switches along the path for that particular burst.

In the Polymorphous OBS (POBS) network architecture recently proposed in [8], BCPs are provided with extended features in order to allow different capacity reservations, rather than conventional fixed-size data bursts. In this light, a given BCP can request the allocation for not only asynchronous data bursts but also for periodic time-slots (subwavelength reservations), and even a complete wavelength over a certain amount of time. This new approach is very attractive for network operators who are willing to provide disparate services with different bandwidth requirements, Quality of Service (QoS) guarantees and transmission scheduling granularities, over the same underlying network infrastructure.

Besides POBS, other OBS-based architectures have been introduced in the literature to allow the reservation of optical resources with subwavelength granularity, see for instance Synchronous OBS (SOBS) [9] and Synchronous-Stream OBS [10]. However, while the former does not allow the reservation of full wavelengths, the latter considers a time-slotted architecture whereby all types of traffic are sent using synchronous channels. Accordingly, the POBS architecture outstands over the previous approaches due to its flexibility in combining both wavelength

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and sub-wavelength capacity reservations just by extending the attributes of Burst Control Packets. Additionally, the POBS architecture is preferred over the other two since it may benefit from the extensive research carried out on JET-based Optical Burst-Switched networks over the past decade.

In spite of its promising features, the performance of POBS has not yet been analysed in detail by the research community. Only the authors in [11] have addressed the performance evaluation of POBS in terms of the blocking probability experienced by best-effort data bursts, generated by a size-based burst assembler [6], when one of such synchronous reservations exist over a single wavelength. However, there is still a need for providing a complete performance evaluation study of generic network topologies with more than one TDM reservation per optical fibre. This is one purpose of this article.

Essentially, the forthcoming sections propose how to adapt the Erlang Fixed Point (aka EFP) iterative procedure to derive the blocking probabilities experienced by best-effort data bursts in a given Polymorphous OBS network topology. The EFP procedure, introduced back in the 1980s (see [12]) has been extensively studied in the literature [13]–[16] and it has been found to accurately model the performance behaviour of circuit-switched networks at low loads. A further study by the authors in [17] extended the conventional circuit-switched formulation of the original EFP to the analysis of Optical Burst Switching following the JET signalling. The reader is also referred to [18], [19] as other examples of the applicability of the EFP procedure in the performance evaluation of OBS networks. Our study takes one step further and provides an EFP-based procedure to derive the blocking probability experienced at each link for any POBS network topology, given as inputs its routing matrix, end-to-end offered traffic load matrix and a set of synchronous TDM reservations already scheduled. Thus, this study sets the grounds for the performance evaluation of the POBS architecture described in [8], and further provides a set of metrics that help network operators decide when to migrate to POBS.

The remainder of this work is organised as follows: Section II briefly reviews the Polymorphous OBS architecture. Section III derives an equation for the blocking probability experienced at a POBS node and shows how to adjust the EFP procedure for evaluating the performance of POBS network topologies. Section IV presents a set of numerical examples to show the applicability of such modified EFP procedure. Finally, Section V summarises the main contributions of this work.

II. Polymorphous OBS Review

A. Architecture Review

The Polymorphous, Agile and Transparent Optical Network (PATON) architecture proposed in [8] aims at the integration of all possible data services on a single optical network technology, ranging from best-effort packet traffic to all optical circuit switching. To this end, [8] proposes to design the future optical nodes upon an extension of OBS and GMPLS, called Polymorphous OBS (POBS), suitable for bandwidth provisioning at any feasible granularity. In principle, POBS can be considered as a “superset” that includes the services provided by the two most relevant circuit-switched technologies driven by GMPLS:

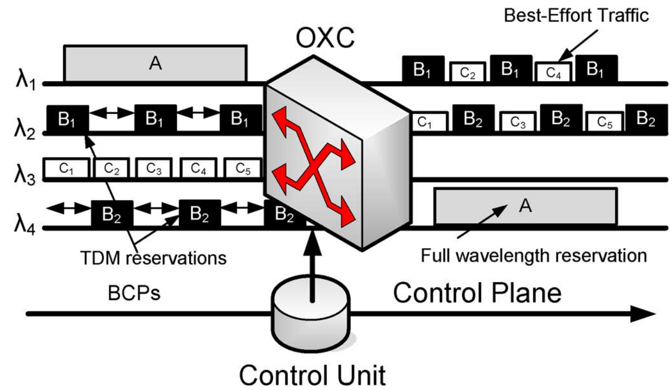

Fig. 1. Example of a POBS switch handling different types of services: A full-wavelength (A), two periodic reservations (B_1 and B_2) and best-effort data bursts ($C_1 - C_5$).

Optical Circuit Switching (OCS or “lambda” switching) and synchronous TDM (SDH/SONET) transport. To support OCS, GMPLS needs no extension under POBS, but just the integration of its control plane with POBS since both mechanisms share the same transmission resources. However, unlike in regular GMPLS, in POBS the support of sub-wavelength synchronous circuits is not based on SDH/SONET, but on periodic reservations that the POBS burst scheduling process makes compatible with other types of asynchronous traffic, the well-known data bursts of conventional OBS. This TDM circuit emulation mechanism reduces inter-node synchronisation requirements in comparison to SONET/SDH and allows taking advantage of full optical switching in the data plane.

In the light of this, Fig. 1 illustrates a typical example whereby a given core Polymorphous OBS switch with full wavelength conversion capabilities handles different types of optical wavelength reservations: (A) A complete wavelength reservation; (B) Periodically-reserved time-slots; and, (C) asynchronous best-effort data bursts.

As shown in the figure, some of the asynchronous data bursts, which arrive at the OXC over wavelength λ_3 are switched to wavelength λ_1, taking advantage of the free gaps in between the periodic reservation B_1, whereas the remaining asynchronous data bursts are switched to wavelength λ_2 since they fit in the gaps left by the TDM reservation B_2. This clearly brings a more efficient use of the network resources since wavelength λ_1 and wavelength λ_2 at the switch’s output allocate the asynchronous data bursts of wavelength λ_3 at the input, bringing a spare wavelength at the switch’s output: wavelength λ_3. Such flexibility in scheduling different reservations is possible since the BCPs are sent a given offset-time in advance in order to configure the intermediate nodes in the source-destination path, and contain a detailed description of the resources needed and their scheduling time-slots.

B. Extended Attributes of BCPs in POBS

Fig. 2 outlines the fields of BCPs with extended attributes for the POBS architecture proposed in [8]. It is worth noticing that some fields are dedicated to routing information but some others contain specific information concerning bandwidth requirements. The former comprise: Label, Type of Control,

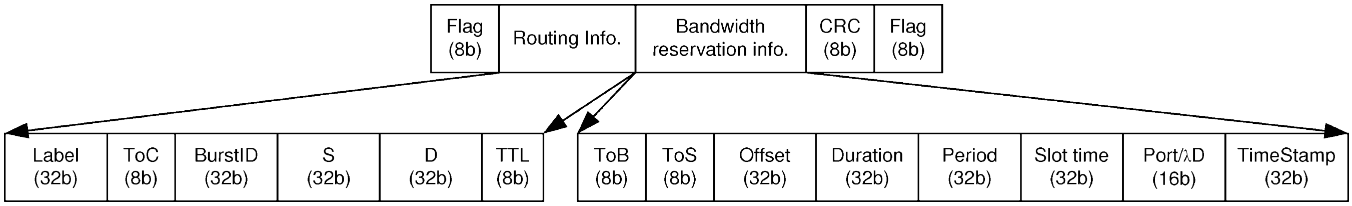

Fig. 2. Summary of the extended fields of BCPs used in the POBS architecture.

Burst ID, Sequence Number, Source and Destination Address and Time To Live. The service requirements related values are: Type of Burst which specifies the type of service required (complete wavelength, periodic reservation or asynchronous data burst); Type of Service, a QoS-related metric which permits distinguishing between different service priorities; Offset time and Duration which refer to the reservation start and finishing times; the Period and Slot time values which are necessary for synchronous TDM services; the Port/Wave ID field which specifies the arrival port or wavelength; and a Timestamp field which stores the arrival time of the setup packet.

Concerning notation for synchronous reservations, let $T_{\rm on}$ denote the length of the transmission (active) periods and $T_{\rm off}$ refer to the duration of the idle periods in between two consecutive "on" periods. Hence, a synchronous reservation is completely specified by the BCP's Period field, which specifies the value of $T_{\rm on}+T_{\rm off}$, the Slot time which refers to $T_{\rm on}$ only, and Duration which denotes the amount of time whereby such TDM reservation occurs.

C. Comparison Between POBS and Parallel Hybrid OBS-OCS

Let us consider an optical network operator which is willing to provide both full wavelength and periodic sub-wavelength reservations with absolute service guarantees, that is, no loss and low bounded delay, together with asynchronous best-effort traffic, whereupon the operator may further define IP differentiated service classes. Examples of services that need either a full wavelength reservation or a periodic portion of it include: SDH/SONET VC transport, IP Television broadcasting, the transmission of VoIP trunks of phone calls, high-speed circuit emulation for third parties, etc.

The need for this high-class virtual circuit-switched transport service, together with the current limitations of OPS and OBS technologies, has boosted research on hybrid optical approaches, see for instance [20]–[23]. Such architectures propose to combine wavelength-switched transport and highly dynamic OBS traffic over shared WDM resources. Although different names are used, all of them pursue the same goal, and shall be referred to as *Parallel Hybrid OBS-OCS* in the following. In such Parallel Hybrid OBS-OCS architectures, a number of wavelengths are reserved for the transmission of high-class virtual circuit-switched service, which are served via OCS. On the other side, best-effort traffic run completely isolated on a different set of wavelengths, which are exploited in OBS mode.

As previously stated, in POBS all wavelengths in the network are exploited in OBS mode but periodic TDM reservations are given absolute priority over best-effort traffic and delivered through a periodic timeslot reservation. The main benefit

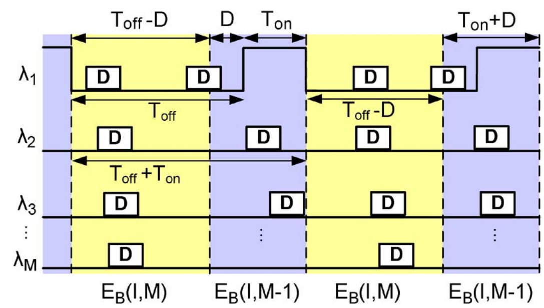

Fig. 3. Example of data bursts coexisting with a single periodic reservation.

of POBS is that best-effort traffic can take advantage of the gaps in between two "on" periods of a sub-wavelength periodic reservation, which further results in a better transmission efficiency and performance of POBS over the Parallel Hybrid OBS-OCS architecture, since the latter requires a full-wavelength reservation for the transmission of such periodic traffic streams. This performance difference shall be evaluated in the experiments section making use of the Erlang Fixed Point algorithm, which is introduced next.

III. Analysis

The following shows how to adapt the iterative Erlang Fixed Point (EFP) algorithm to evaluate the performance of POBS networks, whereby periodic subwavelength reservations coexist with asynchronous data bursts, as shown in Fig. 1. Before revising the EFP algorithm, the following aims to characterise the blocking probability experienced by such asynchronous burst arrivals on a core POBS switch with periodic TDM reservations.

A. On Scheduling Fixed-Size Data Bursts and Performance Evaluation

Let us consider an M-wavelength optical fibre with a single synchronous reservation characterised by its active and idle periods of transmission, that is, $T_{\rm on}$ and $T_{\rm off}$ respectively, as shown in Fig. 3. Data bursts are assumed of fixed duration D (in units of time), typically much smaller than the gaps in between two active periods of the periodic TDM reservation, that is, $D \leq T_{\rm off}$. It is important to remark that fixed-size data bursts are typically generated by size-based burst assemblers in OBS networks.

As shown in Fig. 3, it is assummed that all active periods of a given synchronous reservation are scheduled over the same wavelength, and that asynchronous data bursts are first tried to be allocated on the idle periods if possible, and over a different wavelength otherwise. This shall be referred to as First-Fit scheduling of best-effort traffic onwards. Different scheduling strategies have been analysed in detail in a previous work by the authors (see [11] for more details), showing the First Fit strategy to outperform over other ones. In addition, such previous study [11] provides an analytical approximation for the blocking probability experienced by asynchronous data bursts in such scenario, given by

$$B^{POBS}(I,M) = \frac{T_{\rm on}+D}{T_{\rm on}+T_{\rm off}} E_B(I,M-1) + \frac{T_{\rm off}-D}{T_{\rm on}+T_{\rm off}} E_B(I,M), \quad D < T_{\rm off} \quad (1)$$

which was validated with extensive simulations. Here, I refers to the offered traffic intensity of asynchronous data bursts, in Erlang, M denotes the number of wavelengths and the Erlang-B equation is given by

$$E_B(I,M) = \frac{\frac{I^M}{M!}}{\sum_{k=0}^{M} \frac{I^k}{k!}}. \quad (2)$$

Intuitively, (1) takes into account the cases whereby a random burst arrival occurs during either an active or an idle period. In the case of burst arrivals during an active period of TDM transmission, the blocking probability experienced is approximated by the Erlang-B formula with $M-1$ wavelengths (one wavelength is reserved by the TDM service). Similarly, if the burst arrival occurs during an idle period, the blocking probability experienced is given by the Erlang-B formula with M wavelengths available. Obviously, the two cases must be weighted by the probabilities to arrive during an "on" and an "off" period of TDM transmission.

Basically, random burst arrivals occur during an active period with probability $p = (T_{\rm on} + D)/(T_{\rm on} + T_{\rm off})$, and over idle periods with probability $1-p = (T_{\rm off}-D)/(T_{\rm on}+T_{\rm off})$. This is a consequence of the well-known PASTA (Poisson Arrivals See Time Averages) property, as demonstrated in [24]. It is worth noticing that, although the duration of the active periods is $T_{\rm on}$, the actual portion of time over which a random arrival sees only $M-1$ available wavelengths is actually $T_{\rm on}+D$. This is because burst arrivals must occur D units of time before the beginning of the active period in order to find M wavelengths available, otherwise the burst tail overlaps with the TDM reservation, as shown in Fig. 3.

Finally, without loss of generality, (1) assumes that all data bursts have fixed (i.e., constant) offset-time values, hence the Erlang-B loss formula can be applied to the computation of the blocking probability in both cases, as shown in [25]. For generic offset-time values, the Erlang-B equation does not capture the retroblocking effect [26] that occurs in OBS networks. In such cases, the $E_B(\cdot)$ equations above should be replaced by the appropriate blocking probability equations experienced by I Erlangs of best-effort traffic with M and $M-1$ wavelengths available.

B. *Extension to Several TDM Reservations and Variable-Size Data Bursts*

Eq. (1) can be further extended to the case whereby several wavelengths contain a synchronous reservation each, and data bursts are of variable size as generated by timer-based burst assemblers. Fig. 4 shows an M-wavelength optical fibre which contains three synchronous reservations with different active and idle period lengths, together with asynchronous data bursts. Let $K \le M$ denote the number of wavelengths with one of such periodic reservations, and let $T_{on,j}$ and $T_{off,j}$ refer to the duration of the active and idle periods respectively for the reservation over wavelength j, with $j = 1,\ldots,K$. In this case, a random data burst arrival finds the j-th wavelength occupied by the synchronous reservation with probability p_j

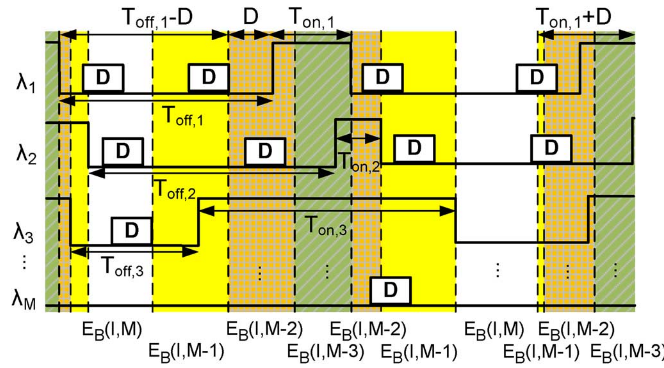

Fig. 4. Example of data bursts coexisting with several periodic reservations.

$$p_j = \frac{T_{{\rm on},j}+E[D]}{T_{{\rm on},j}+T_{{\rm off},j}} \quad (3)$$

as explained above. Here $E[D]$ stands for the average burst size in units of time.

Assuming that all synchronous reservations are independent, a given random burst arrival finds no wavelength reserved by a synchronous reservation with probability R_0

$$R_0 = \prod_{j=1}^{K}(1-p_j), \quad K \le M$$

Accordingly, a random burst finds one wavelength already reserved by a synchronous service with probability R_1:

$$\begin{aligned} R_1 &= (1-p_1)(1-p_2)\cdots(1-p_{N-1})p_N \\ &\quad + (1-p_1)(1-p_2)\cdots p_{N-1}(1-p_N) + \ldots \\ &\quad + p_1(1-p_2)(1-p_3)\cdots(1-p_N) \\ &= \sum_{i=1}^{K} p_i \prod_{\substack{j=1 \\ j\neq i}}^{K}(1-p_j), \quad K \le M \end{aligned} \quad (4)$$

which takes into account all possible cases whereby one wavelength is occupied and the other $K-1$ are free. Similarly, the cases whereby a random data burst finds two wavelengths occupied by TDM reservations, R_2, is given by a double sum

$$R_2 = \sum_{i_1,i_2}^{K} p_{i_1}p_{i_2} \prod_{\substack{j=1 \\ j\neq i_1,i_2}}^{K} (1-p_j) \quad (5)$$

Finally, for any number of wavelengths with synchronous TDM reservations $k = 1, \ldots, K$ the above equations are summarised with

$$R_k = \sum_{i_1, i_2, \ldots, i_k}^{K} p_{i_1} p_{i_2} \cdots p_{i_k} \prod_{\substack{j=1 \\ j \neq i_1, i_2, \ldots, i_k}}^{K} (1 - p_j). \quad (6)$$

It is worth noticing that, if all synchronous reservations have the same T_{on} and T_{off} values, (6) reduces to a binomial distribution given by

$$R_k = \binom{K}{k} p^k (1 - p)^{K-k} \quad (7)$$

where $p = (T_{\text{on}} + E[D])/(T_{\text{on}} + T_{\text{off}})$.

Thus, the blocking probability experienced by I Erlangs of asynchronous burst traffic offered to a POBS node with K periodic reservations is approximated by a weighted Erlang-B equation as follows, as a consequence of the Poisson Arrivals See Time Averages (PASTA) property

$$B^{POBS}(I, M, K) = \sum_{k=0}^{K} R_k E_B(I, M - k), \quad K \leq M \quad (8)$$

Clearly, (8) extends the case whereby a single wavelength is reserved by a synchronous service, given by (1). The example in Fig. 4 shows the regions where $E_B(I, M)$, $E_B(I, M - 1)$, $E_B(I, M - 2)$ and $E_B(I, M - 3)$ applies.

Concerning the Parallel Hybrid OBS-OCS architecture, the equation above reduces to

$$B^{OBS-OCS}(I, M, K) = E_B(I, M - K), \quad K \leq M \quad (9)$$

when K TDM reservations are present, and I Erlangs of best-effort traffic must share the remaining $M - K$ wavelengths.

Finally, (8) and (9) shall be used next to modify the Erlang Fixed Point algorithm in the performance analysis of POBS networks.

C. POBS-Modified Erlang Fixed Point Algorithm

Let $G(N, L)$ denote a given network topology characterised by N POBS nodes, and a total number of links L. Let l_i denote the i-th link in the network, with $i = 1, 2, \ldots, L$, and let I_j, $j = 1, \ldots, J$, with $J \leq N^2$ denote the j-th end-to-end traffic offered between any pair of nodes in the network, that is, for end-to-end network route r_j. Also, let B_{l_i} denote the blocking probability experienced by link l_i and B_{r_j} denote the end-to-end blocking probability observed by traffic traversing route r_j. Finally, let the input traffic be assumed to follow a Poisson process.

In the case of Poisson traffic, for mathematical tractability, it is generally accepted the assumption that blocking events occur independently from link to link along any end-to-end route r_j, see for instance [12], [13], [15], [16]. If this is the case, the Erlang Fixed Point (EFP) algorithm, firstly introduced by F. P. Kelly in the 1980s [12], provides an iterative algorithm to derive the blocking probability experience by each link in the network and, consequently, the traffic actually carried by any link. This algorithm is summarised as follows:

1) Start the algorithm with a random set of link blocking probabilities $B_{l_i} \in (0, 1]$, with $i = 1, 2, \ldots, L$.
2) With values B_{l_i}, obtain the end-to-end blocking probability for route r_j, B_{r_j} as

$$1 - B_{r_j} = \prod_{i \in r_j} (1 - B_{l_i}), \quad j = 1, \ldots, J \quad (10)$$

which arises as the product of individual non-blocking probabilities of the links traversed by route r_j, given the assumption of independent link blocking.

3) The end-to-end blocking probability set B_{r_j}, with $j = 1, \ldots, J$, determine the amount of asynchronous data bursts traffic actually carried by each individual link I_{l_i}, given by

$$I_{l_i} = \sum_j I_{r_j} \prod_k (1 - B_{l_k}), \quad l_i \in r_j, \quad l_k \text{ before } l_i \quad (11)$$

which takes into account the total amount of traffic offered to link l_i. This quantity I_{l_i} is computed as the sum of all end-to-end traffic intensities I_{r_j} offered at l_i (in other words, satisfying $l_i \in r_j$), and taking into account the blocking probability experienced at every link l_k before link l_i.

4) Finally, the blocking probability experienced by each link B_{l_i} in the network is updated with offered traffic I_{l_i} applying (8) derived in the previous section

$$B_{l_i} = B^{POBS}(I_{l_i}, M_{l_i}, K_{l_i}) \quad (12)$$

whereby M_{l_i} and K_{l_i} refer to the total number of wavelengths available and TDM reservations on link l_i.

5) Return to step 2 making use of the new set of link blocking probabilities B_{l_i}, $i = 1, \ldots, L$, and repeat until convergence.

The reader is referred to [12] for a detailed analysis of the EFP iterative loop above. It is important to remark that (11) has been modified from the original study by Kelly *et al.* to deal with the fact that, when using a one-way reservation algorithm such as JET, the traffic offered to link l_i depends on the blocking probability of all links l_k which preceed l_i within route r_j, as described in [17].

Finally, it is worth emphasising the use of (8) as a substitute for the original Erlang-B equation in step number 4, which permits the use of EFP to the performance analysis of POBS networks. Such equation should be replaced by (9) in the analysis of the Parallel Hybrid OBS-OCS architecture.

Concerning the convergence behaviour of the POBS-modified EFP procedure, the reader should note that the algorithm above maps a vector of blocking probabilities $B^{N_{it}}$ at iteration N_{it} into a new vector $B^{N_{it}+1}$, via the mapping

$$T_{l_i}\left(B_{l_i}^{N_{it}+1}\right) = \sum_{k=0}^{K_{l_i}} R_{k_{l_i}} E_B\left(\sum_j I_{r_j} \prod_n \left(1 - B_{l_n}^{N_{it}}\right), M_{l_i} - k\right)$$
$$l_i \in r_j, \quad l_n \text{ before } l_i \quad (13)$$

More precisely, the transformation $T(B)$ of blocking probabilities is continuous and maps the compact set (0,1] to the same (0,1] set, therefore there is at least one fixed point (Fixed Point

Theorem). To ensure the uniqueness of such a fixed point, $T(B)$ is required to be a contraction map, that is, the distance between any two solutions for B reduces every time the transformation is applied (that is, after every iteration) [27].

The reader can find a similar discussion concerning the convergence of the EFP procedure applied to OBS in [17]. The POBS-modified transformation defined in (13) just weights the blocking probabilities B_{l_i} by factor R_k in (6) which does not depend on the blocking probabilities themselves but only on the ratio $p = (T_{\rm on} + E[D])/(T_{\rm on} + T_{\rm off})$. According to this, the transformation defined in (13) is also a contraction map since it is a weigthed average of contraction maps, therefore the fixed point is unique.

Finally, it is just necessary to apply the transformation iteratively up to the point where the distance between consecutive blocking probability outcomes fall below a given threshold, and the fixed point is obtained. This convergence behaviour of the POBS-modified EFP algorithm is further studied in the experiments section.

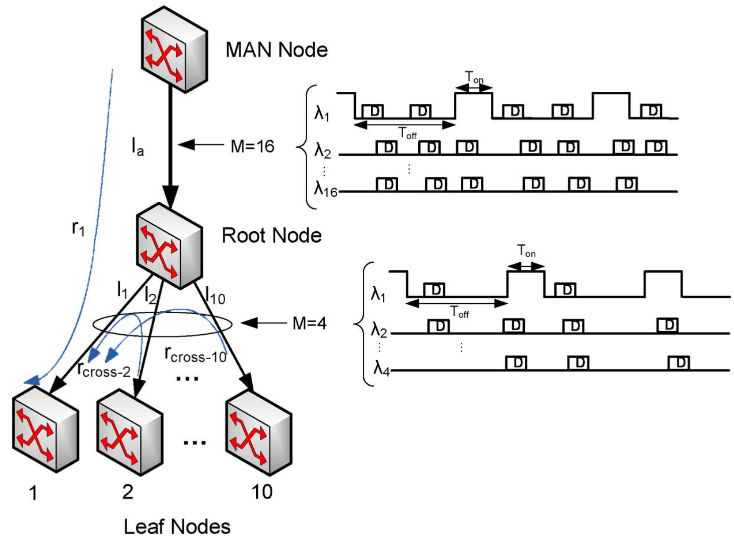

Fig. 5. IPTV tree scenario.

IV. Numerical Examples

The following sections present two scenarios whereby a POBS architecture might be an interesting choice for network operators. The former experiment considers the broadcasting of IP Television to its customers. The IPTV signal arrives at a root node which distributes the IPTV channels down to its customers who are connected to it following a traditional tree topology. The second experiment considers a case whereby a network operator provides synchronous bandwidth-guaranteed TDM reservations to service providers.

Both experiments aim to compare the benefits of using POBS with respect to the Parallel Hybrid OBS-OCS architecture proposed in the literature, and further validate the POBS-modified EFP procedure presented in Section III with simulation results.

A. Distribution of IPTV Over a Tree Topology

This first example considers the tree topology shown in Fig. 5 which is typically used for the distribution of IP TeleVision traffic to a metropolitan area. Essentially, IPTV traffic arrives at the root node which further distributes it to all those leave nodes which have previously joined a given multicast group via IGMP. If employing the POBS architecture, the IPTV traffic could be transmitted down to the leaves over periodic TDM reservations, together with asynchronous data bursts.

Let us consider a root node which interconnects ten leaves via 4-wavelength optical fibres, as shown in the Fig. 5. The root node is connected to the upper MAN node via a 16-wavelength optical fibre. For the experiments, we have also considered the transmission of $N_{ch} = 192$ Standard Definition TV channels, that is, of bitrate $R_{ch} = 4.16$ Mbits/s per channel with MPEG-2 encoding which, over a $C = 10$ Gbps wavelength, comprise the following percentage duration:

$$\frac{N_{ch}R_{ch}}{C} = \frac{192 \times 4.16 \cdot 10^6 \text{ bits/sec}}{10 \cdot 10^9 \text{ bits/sec}} \approx 0.08. \quad (14)$$

That is, about 8% of the total capacity of a single wavelength is guaranteed for the transmission of IPTV traffic (about 800 Mbits/s). This leaves the remaining 92% of total capacity for the transmission of asynchronous data bursts. Assuming active periods occur every 2.5 ms, as measured from a Spanish IPTV service provider (see [11] for further details), the $T_{\rm on}$ and $T_{\rm off}$ periods are given by

$$\begin{aligned} T_{\rm on} &= 0.08 \times 2.5 \text{ ms} = 0.2 \text{ ms} \\ T_{\rm off} &= (1 - 0.08) \times 2.5 \text{ ms} = 2.3 \text{ ms}. \end{aligned} \quad (15)$$

Finally, data bursts are assumed of 100 KBytes of fixed size, thus the duration is:

$$D = \frac{8 \times 100 \cdot 10^3}{10 \cdot 10^9} = 80\ \mu\text{s} \quad (16)$$

which is much smaller than the value of $T_{\rm off}$. Assuming, data bursts arrive at the root node following a Poisson process with rate λ bursts/sec, the offered traffic intensity I is given by $I = \lambda E[D]$ Erlangs. The experiment assumes that the MAN node generates such asynchronous best-effort traffic I which, upon its arrival at the root node, is further distributed to the 10 leaf nodes in the same proportion. Additionally, each leaf node is assumed to generate the amount $I_{L2L} = 0.1$ Erlang of traffic destined to the other leaves. According to this, the amount of total traffic offered at link l_1, I_{l_1}, comprises the portion of best-effort traffic coming from the MAN node (after blocking observed on link l_a) together with the Leaf-2-Leaf traffic generated from the other 9 leaf nodes.

Following these assumptions, Fig. 6 shows the end-to-end blocking probability experienced on route $r_1 = \{l_a, l_1\}$ shown in Fig. 5, which goes from the upper MAN node to the leaf node number 1. The results aim to compare the blocking probability observed with POBS together with the results for a Parallel Hybrid OBS-OCS architecture (see Section II-C), and further validate the theoretical model with simulation results. As shown, the blocking probability experienced by asynchronous data bursts is always much smaller when employing POBS (specially at low loads) since such data bursts can take advantage of the gaps in between synchronous reservations.

This benefit can also be expressed in terms of actual end-to-end throughput. To this end, we define the *POBS*

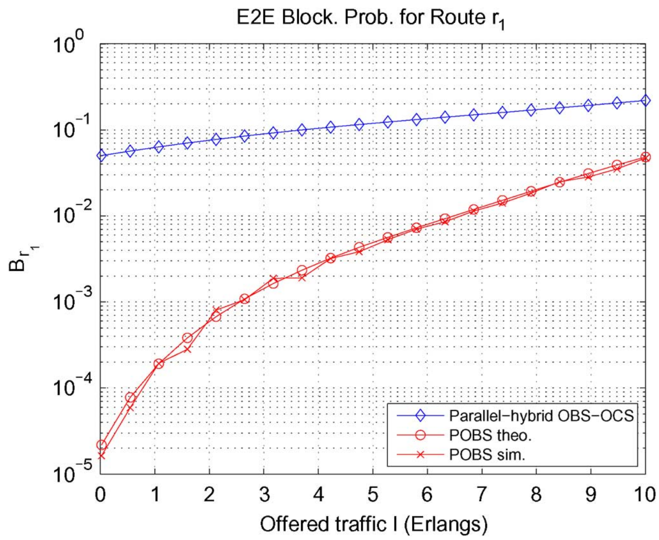

Fig. 6. B_{r_1} for POBS (circles) and parallel hybrid OBS-OCS (diamonds) in the IPTV scenario.

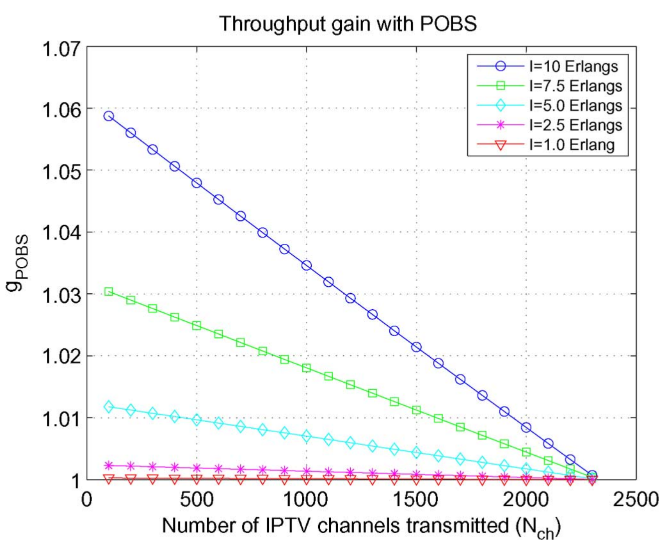

Fig. 7. Throughput gain with variable number of transmitted TV channels.

throughput gain metric, namely g_{POBS}, as the ratio between the total throughput actually carried by the network when using the POBS architecture over the total throughput if the Parallel Hybrid OBS-OCS architecture is employed. This is given by

$$g_{POBS} = \frac{\sum_r I_r \left(1 - B_r^{POBS}\right)}{\sum_r I_r \left(1 - B_r^{OBS-OCS}\right)} \tag{17}$$

for all end-to-end routes $r \in R$.

Obviously, the larger the gaps in between two active periods in a synchronous TDM reservation, the higher the gain g_{POBS} since such gaps are used for carrying asynchronous data bursts. Thus, Fig. 7 shows the actual gain value achieved when using POBS for different IPTV traffic profiles. Such profiles consider the transmission of a variable number of IPTV channels N_{ch}, thus enlarging or shortening the gaps represented by $T_{\rm off}$ as given by (14) and (15).

As shown, if POBS is employed, large values of throughput gain g_{POBS} can be achieved when the number of IPTV channels

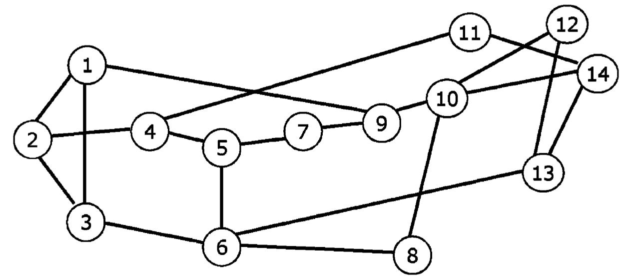

Fig. 8. The NSFnet network topology.

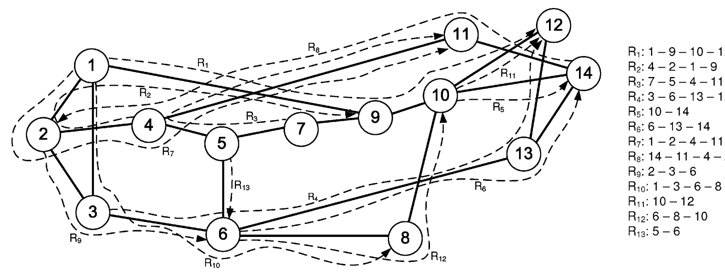

Fig. 9. Selected routes R_1 to R_{13} of NSFnet for analysis validation.

transmitted is small (large values of $T_{\rm off}$), since POBS makes use of the gaps in between two "on" periods.

B. Model Validation for the NSFnet

This experiment aims to validate the analytical POBS-modified EFP procedure with simulations for a large-size network topology: The NSFnet. The NSFnet comprises 14 nodes distributed across the United States of America and 20 links connecting them, as shown in Fig. 8.

The simulation considers three different network load levels: $I_{e2e} \in \{0.4, 0.7, 1\}$ Erlang and $M = 8$-wavelength links in each direction. For instance, the case $I_{e2e} = 0.4$ Erlang/e2e path means that each route offers 0.4 Erlang of traffic, thus a total throughtput of $I_{tot} = I_{e2e}N(N-1) = 0.4 \cdot 14 \cdot 13 = 72.8$ Erlang is offered to the NSFnet, since the total number of paths is equal to $14 \cdot 13 = 182$. However, for brevity purposes, we have only selected thirteen different end-to-end routes R_1 to R_{13} which cover almost all links in the NSFnet (see Fig. 9) and computed their end-to-end blocking probabilities at different load levels (see Table I). Again, the TDM reservation considers the same $T_{\rm on} = 0.2$ ms and $T_{\rm off} = 2.3$ ms as in the tree experiment. As shown in the Table, the difference between the simulated and the theoretical values can be considered within acceptable limits, given the approximation nature of the Erlang Fixed Point methodology (see for instance [17] end of Section IV).

Finally, concerning convergence aspects of the POBS-modified EFP algorithm, Fig. 10 shows the evolution of the absolute blocking probability error $e^{N_{it}}$ versus number of iterations N_{it} at network load: $I_{e2e} = 0.7$ Erlang. This value is computed as follows:

$$e^{N_{it}} = \max_{l_i} \left| B_{l_i}^{N_{it}} - B_{l_i}^{N_{it}-1} \right| \tag{18}$$

which measures the maximum absolute error between every two consecutive iterations, for all links l_i in the NSFnet topology.

TABLE I
END-TO-END ROUTE BLOCKING PROBABILITIES FOR R_1 TO R_{13} (THEORETICAL/SIMULATED)

Route name	0.4 Erlang (theo/sim)	0.7 Erlang (theo/sim)	1 Erlang (theo/sim)
R_1	0.172/0.149	0.492/0.465	0.671/0.665
R_2	0.086/0.080	0.360/0.337	0.575/0.581
R_3	0.113/0.095	0.386/0.354	0.595/0.602
R_4	0.185/0.157	0.476/0.451	0.644/0.630
R_5	0.040/0.036	0.151/0.123	0.244/0.214
R_6	0.065/0.056	0.179/0.160	0.265/0.240
R_7	0.115/0.119	0.405/0.377	0.608/0.606
R_8	0.102/0.083	0.403/0.377	0.620/0.614
R_9	0.128/0.111	0.371/0.361	0.538/0.527
R_{10}	0.164/0.130	0.455/0.429	0.634/0.618
R_{11}	0.035/0.023	0.109/0.074	0.166/0.148
R_{12}	0.045/0.035	0.173/0.160	0.307/0.286
R_{13}	0.080/0.065	0.259/0.258	0.389/0.385

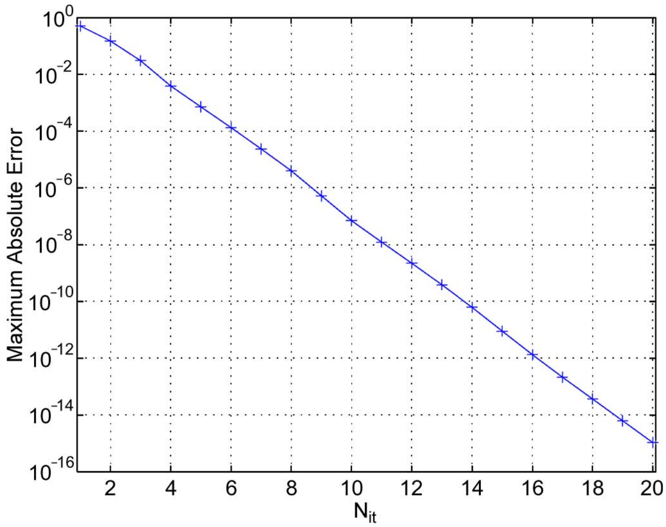

Fig. 10. Evolution of the blocking probability error with number of iterations in the POBS-modified EFP procedure.

Clearly, after a number of iterations ($N_{it} > 10$), the POBS-modified EFP algorithm converges showing very small accuracy increase per iteration.

C. Performance Analysis of the NSFNet

Finally, this set of experiments aims to show the benefits of using POBS with respect to the Parallel Hybrid OBS-OCS architecture in a more realistic scenario, with a large number of wavelengths M and variable number and size of TDM reservations. Thus, the next experiments assume that each link provides $M = 32$ wavelengths of 10 Gbps/wavelength in each direction. Without loss of generality, the periodic reservations have been assumed of TDM load ratio 10% and period $T_{\rm on} + T_{\rm off} = 2.5$ ms, in other words, $T_{\rm on} = 0.25$ ms and $T_{\rm off} = 2.25$ ms. Again, asynchronous data bursts have been generated by a size-based burst assembler with length limit of 100 Kbytes/burst, hence of duration $D = 0.08$ ms.

In the light of this, Fig. 11 shows the throughput achieved assuming four different load scenarios: $I_{e2e} \in \{0.25, 0.75, 1.5, 3\}$ Erlang per end-to-end flow. In Fig. 11, the x axis represents the number of periodic reservations K, ranging from $K = 0$ (no periodic reservation is made) to $K = M = 32$ (all link wavelengths contain a TDM reservation). The y axis gives the total throughput carried for the two architectures under study: (a) The Polymorphous OBS, and (b) the Parallel Hybrid OBS-OCS solutions.

As shown, the POBS architecture carries almost all offered traffic at low-load levels: 45.5 Erlang (Fig. 11 top-left) and 136.5 Erlang (Fig. 11 top-right), and almost all of it in the other two scenarios. The Parallel Hybrid OBS-OCS architecture exhibits a performance very close to POBS, but only when the number of synchronous reservations is small: $K \in [0, 25]$ for low load values (Fig. 11 top-left), $K \in [0, 2]$ for high load values (Fig. 11 bottom-right). Clearly, since the POBS architecture takes advantage of the gaps in between periodic reservations, it achieves larger values of throughput than its counterpart. Indeed, the performance of the Parallel Hybrid OBS-OCS architecture degrades very significantly when increasing the number of periodic reservations K, and is specially remarkable at high-load scenarios (Fig. 11 bottom-right) since the wasted gaps in between periodic reservations become precious.

With these results, the following question arises: Which number of periodic reservations is necessary to have a drastic outperforming of POBS with respect to the Parallel Hybrid OBS-OCS architecture? In other words, we are interested at evaluating the number of periodic reservations over which, POBS offers a substantial performance increase. Let K_{cut} refer to the number of periodic reservations beyond which the throughput experienced in a hypothetical Parallel Hybrid OBS-OCS NSFnet architecture drops 25% with respect to POBS. As shown in Fig. 11, such K_{cut} metric takes the values $K_{cut} = 28$ for asynchronous traffic load $I_{e2e} = 0.25$ Erlang/route (top left), $K_{cut} = 23$ for traffic load $I_{e2e} = 0.75$ Erlang/route (top right), $K_{cut} = 16$ for traffic load $I_{e2e} = 1.5$ Erlangs/route (bottom left) and $K_{cut} = 10$ for traffic load $I_{e2e} = 3$ Erlangs/route (bottom right). Essentially, K_{cut} arises as the minimum number of periodic reservations required in a given scenario (characterised by I and the TDM load ratio $T_{\rm on}/(T_{\rm on} + T_{\rm off})$) such that POBS outperforms by more than 25% of total throughput carried.

The metric K_{cut} should be interpreted as follows: If a network operator is expecting to have a number of periodic reservations $K < K_{cut}$ over a given topology, then there is no significant difference between deploying POBS and the Parallel Hybrid OBS-OCS. Hence, such K_{cut} metric assists network operators to evaluate the feasibility and viability of migrating to a POBS solution or not.

To sum up with these ideas, Fig. 12 shows the values of K_{cut} obtained for several case scenarios. The results show that POBS outperforms the Parallel Hybrid OBS-OCS architecture for large input traffic load I_{e2e} and small TDM load ratios $T_{\rm on}/(T_{\rm on} + T_{\rm off})$.

V. SUMMARY AND DISCUSSION

This work provides a novel performance evaluation of the Polymorphous Optical Burst-Switched network architecture described in [8]. Basically, this architecture extends the attributes

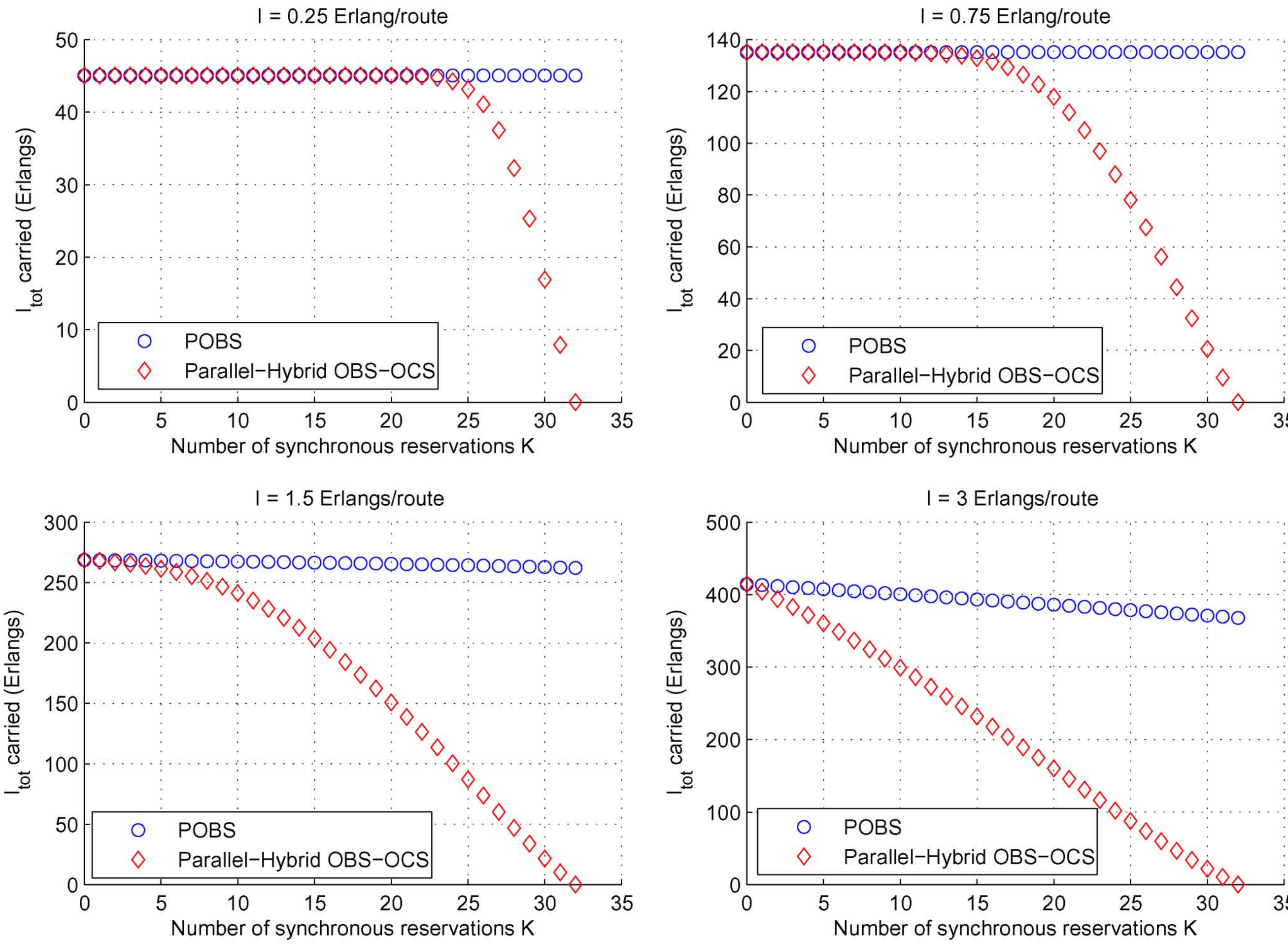

Fig. 11. Total throughput I_{tot} (Erlangs) achieved by POBS (circles) and the Parallel Hybrid OBS-OCS architecture (diamonds) in the NSFnet.

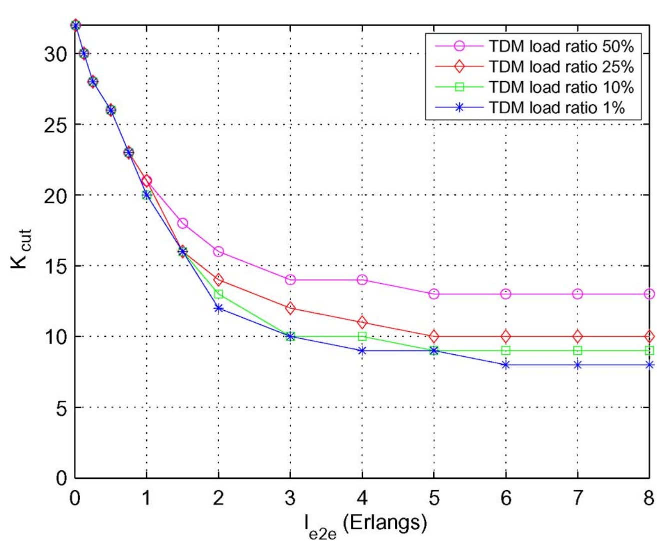

Fig. 12. K_{cut} values arisen in different scenarios for the NSFnet.

of BCPs from conventional OBS networks to allow the reservation of periodic time-slots for the support of guaranteed services with sub-wavelength granularity.

Essentially, the POBS architecture provides a flexible sub-wavelength reservation granularity such that the gaps in between two active periods in a synchronous reservation can be further used for the allocation of asynchronous data bursts, thus making a more efficient use of the available optical capacity with respect to Parallel Hybrid OBS-OCS architectures where a synchronous stream would require the reservation of a full wavelength. The performance evaluation of POBS considers the modification of the well-known Erlang Fixed Point iterative procedure, whereby the blocking probability computed at each link is replaced by a weighted Erlang-B based equation. This equation takes into account the amount of time over which a number of wavelengths are free multiplied by the blocking probability observed when such number of wavelengths is available. Such modified Erlang Fixed Poing algorithm can be used to completely characterise the performance behaviour of POBS over large-size network topologies.

The experiments reveal the outstanding performance of POBS, which provides significant throughput gains with respect to the Parallel Hybrid OBS-OCS architecture, especially when the number of periodic TDM reservations is large and their active periods are small.

Finally, this work concludes with a design rule of thumb, the K_{cut} metric, which is intended to assist network operators in evaluating the feasibility and viability of migrating to POBS architectures. The K_{cut} metric determines the average number of synchronous TDM reservations required which results in a given throughput gain achieved by POBS.

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