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Modeling an Optical Network Operating with Hybrid-switching Paradigms

Invited Paper

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***Abstract*— The continuous increasing of the Internet traffic has brought serious concerns about capacity exhaustion of the optical infrastructure in a medium term horizon. Taking into account the optical networks, comprising the Internet backbone, the strategies to avoid this catastrophic scenario point to the development of new technologies that enable the capacity expansion, as well as to a better utilization of network resources (spectrum or wavelengths). The elastic optical network, considered as a realistic perspective for the infrastructure, optimizes the required spectrum and improve the efficiency of resources utilization. However, it is based on optical circuit switching paradigm that tends to waste resources due to idle times of reservation process. Since in some dedicated optical networks, like data center networks, certain optical switching paradigms have become reality, it is expected that in the coming years not only an elastic optical network, but also a hybrid network, in terms of switching paradigms, be brought to reality. Considering this scenario, the present paper addresses some issues on the modeling of an optical network working with hybrid-switching paradigms.**

***Index Terms*—** Optical Network Modeling, Optical Switching Paradigm, Hybrid Operation.

I. INTRODUCTION

In recent years, the world has experienced the global adoption of many bandwidth-hungry applications, such as Internet protocol television (IPTV), high definition video-on-demand and real-time communications, which contribute to a continuous increasing of network traffic. Moreover, the Internet of things (IoT) is expected to be practical in the short term and it will consume an additional amount of bandwidth. Based on the data obtained from backbone reference networks, operators estimate a future annual growth rate of Internet traffic around 35% [1], pressuring the optical networks to provide higher capacities with more flexibility and lower costs. In this scenario, a redesign of optical infrastructure based on wavelength division multiplexing (WDM) is required to postpone the inevitable capacity crunch.

Elastic optical network (EON) [2]-[4] has become an option that enables a higher spectrum utilization, assigning spectrum slices as a function of bandwidth service demands, and dealing better

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with uneven spectrum requirements than the conventional fixed grid WDM network. According to [5], the realization of EON is considered a realistic perspective since (i) it can seamlessly be deployed, (ii) it optimizes the required optical spectrum, and (iii) it provides flexibility with minimum disruption to the existing infrastructures, due to Sliceable Bandwidth-variant Transponders (S-BVT) and Flexible Optical Cross-connect (Flex-OXC). Therefore, EONs are expected to contribute to improving the resource utilization efficiency. However, the EON suffers with its own problems, and the most known problem in EONs is the spectrum fragmentation [6]. This problem comes from the dynamical nature of Internet traffic, which is affected by the connection lengths, distribution of bandwidth demands, and connection hold and idle times. The connection lengths can range from few tens to several thousands of kilometers, in single-hop or multi-hop routes, filling the spectrum (on connection setup) or leaving spectrum voids (on connection release) along all the used network links. The bandwidth requests, which can be from tens to hundreds of GHz, are related to the bit rate, according to the spectral efficiency of a given modulation format. Consequently, releasing different kinds of connections may leave spectrum voids with different sizes. Moreover, connection hold and idle times can be statistically distributed around an average value, which may range from seconds (as a conventional IP packet) to hours or even longer timescales. The last aspect is common in EONs and traditional WDM networks, since both are based on optical circuit switching (OCS). Around the first years of this century, one of the main targets was the development of efficient approaches to achieve higher levels of statistical multiplexing in the optical layer. Thus, the optical packet switching (OPS) was proposed as a promising solution to bring the advantages of WDM network (already deployed in the Internet core) to the metropolitan network (MAN) [7]-[9]. The main issue was that OPS could provide a better adaptation in a truly dynamic environment, where the infrastructure costs are dominant and traffic of several kinds of service needs to be carried.

A great effort was spent to make the OPS practical, allowing traffic delivery in MAN [10]-[14]. However, some technological constraints turned difficult the management and the implementation of contention resolution schemes. Among them, the missing of ultrafast switching fabrics, lack of functional optical memories, and immaturity of optical processing, contributed to make the OPS a utopic metropolitan optical network. Because of these problems, the optical burst switching (OBS) was proposed to mitigate some of the OPS problems, like the need for fast processing and switching, behaving as a switching paradigm with shared characteristics from OCS and OPS [15][16]. On the other hand, the adaptability of optical transport network (OTN) contributed to keep OPS and OBS technologies confined in the testbeds and theoretical research, besides their innovative potential [17][18]. Nevertheless, the development of optical switching devices technologies in the last few years [19], the appearing of software defined network (SDN) technology, and the need to handle and store great volumes of traffic [20], generally using large-scale data center networks (DCN), brought back the interest in OPS [21]-[23]. Currently, experiments have shown the advantages of using hybrid-switching paradigms like OCS and OPS to virtualize resources in DCNs, by using concepts in

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EONs [22][23]. In addition, some studies on hybrid optical networks [24]-[27] demonstrated the improvement of quality, granularity and throughput efficiency, pointing to a medium term horizon where it finally may have an optical network operating simultaneously with multiple switching paradigms. This work presents some issues on such networks modeling, providing tools to carry on a performance analysis.

The rest of this paper is organized as follows. Section II deals with the existing optical switching paradigms with their most known reservation processes and the main issues on a network modeling. Section III presents the most known performance parameters regarding optical networks and the methodology to get them. Section IV brings the model for a hybrid-switching optical network and presents a brief discussion on it. Section V shows the results regarding the adopted scenario of a hybrid-switching network and Section VI presents the conclusions remarks.

II. Optical Switching Paradigms

The known optical switching paradigms (OCS, OPS and OBS) work in different ways in an optical network, mainly when considering the taking time to setup the connections or to reserve resources for transmitting information data. In the OCS case, the setup process can be performed in a centralized or decentralized way, depending on if each node has only the information about its resources or if there is a root node that manages the resource information on an entire network domain. Moreover, the transmission of data in OCS paradigm starts only after the resource reservation along a route is confirmed. On the other hand, OPS and OBS usually do not have a resource confirmation before transmitting data from a source node. This happens because they perform the reservation process in a decentralized hop-by-hop way, on which each node manages its own resources and switching devices. Since a modeling to a hybrid-switching network will be further presented, in order to avoid conflicting information among switching paradigms, all of them are treated in a decentralized way.

A. Optical Circuit Switching

The OCS paradigm works based in resource-oriented way, on which a lightpath is established only when there is at least a unique free resource (used as synonymous of wavelength) available in all links of a given route between a source node and a destination node. Given that a resource is assigned to a connection (or lightpath), it is only released after all the data are sent to the destination node [28]. The time for the effective connection establishment depends on the delay time (or propagation time) and on the time for information processing on each link. The delay time is related to the data travelling time on a specific link, and it depends on the link distance and on the phase velocity of the electromagnetic wave propagating in the optical fiber. The time for information processing (setup time) depends on the node hardware and on the amount of node resources. Usually, it is a time estimative to process the information and to prepare the signaling message to the next node. The OCS signaling scheme is generically presented in Fig. 1, in which a connection is assigned between node 1

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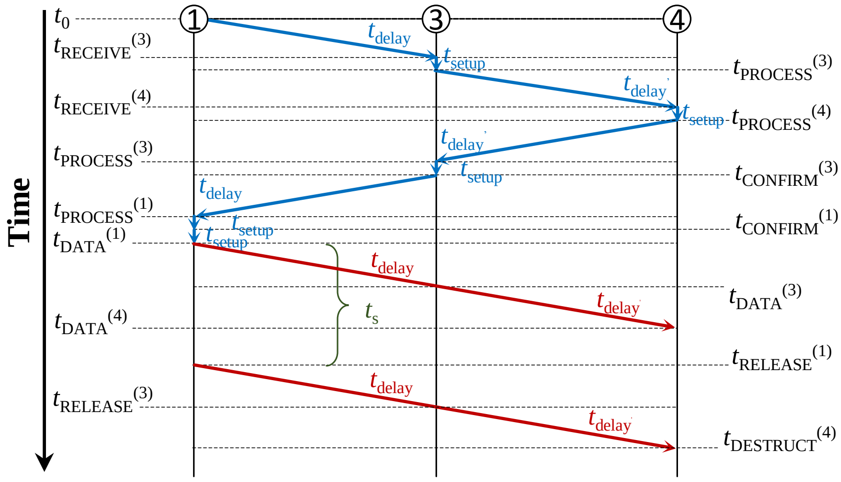

Fig. 1. Optical circuit switching connection establishment.

and node 4, passing through node 3. In this case, the route is 1 → 3 → 4. At t_0, all information about free resources on link 1 → 3 are sent to node 3. It must be noted that since free resources on whole route are unknown at this time, all of them are made busy for a future reservation propose. Some techniques of generalized multiprotocol label switching (GMPLS) allowing RSVP-TE (resource reservation protocol - traffic engineering) do not make the resources busy in advance, but with the drawback of having a possibility of taking a wrong decision at destination node, since, in this case, some of previous free resources can be chosen for other lightpath during the connection establishment process. Sequentially, to achieve node 3, the list of available resources takes t_{delay}, arriving there at $t_{RECEIVE}^{(3)}$ (the superscript indexes indicate the processing node). After arriving, node 3 takes t_{setup} time units to (i) process the arriving information, (ii) get its particular list of available resources and (iii) prepare the signaling to the next node (node 4), according to routing information and containing only the list of resources that are free on both links 1 → 3 and 3 → 4. Further, only if there is the same free resource in both links, these tasks are finished at $t_{PROCESS}^{(3)}$ and the information is sent to node 4. Else, a BLOCK message is sent back to node 1, reserving no resource at link 3 → 4. Given that there is at least one free resource on both links, after t_{delay}' (generally different from t_{delay} due to link distances) the destination node receives all the information to setup the connection, at $t_{RECEIVE}^{(4)}$, and will process it during t_{setup}. The processing at destination node is very important since it will receive the list of available resources along the whole route and will choose one of them, based on an assignment strategy, like First-Fit, Random-Fit, Most-Used and so on. The other nodes must be informed about the chosen resource, so at $t_{PROCESS}^{(4)}$ this information is sent to node 3. When this information arrives, node 3 makes free all the resources previously reserved for the connection, unless the chosen resource at destination node. At $t_{CONFIRM}^{(3)}$, after t_{setup}, a message is sent to node 1 which, up to $t_{CONFIRM}^{(1)}$, processes the list of previous reserved resources and the chosen wavelength, just like node 3. The connection will begin to transmit data after t_{setup} from this time, at $t_{DATA}^{(1)}$. Moreover, if node 1 receives a BLOCK message, the connection will be rejected at $t_{DATA}^{(1)}$, after releasing the

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previous reserved resources at $t_{\text{CONFIRM}}^{(1)}$. For modeling proposes, considering a connection with service time t_s, node 1 will release the connection t_s time units after $t_{\text{DATA}}^{(1)}$, by assuming that all the nodes are equipped with an automatic data detection. As an additional feature, it could be considered a processing time for connection releasing, but it was ignored for the present model. Furthermore, considering a simulation procedure, a connection destruction event happens in the releasing process at destination node (considered as the time that all the data is already transmitted), when all the recorded data, regarding a specific connection, can be removed from memory.

As can be seen, during the connection establishment process some resources are made busy, but they are not used at that time for data transmission. Therefore, the concept of idle time is introduced. The idle time will appear in any optical switching paradigm with different magnitudes. The idle times for different nodes in a given route can be different. For instance, Fig. 1 shows that the idle time at node 1 (hop zero) can be given by $t_{\text{DATA}}^{(1)} - t_0$, which is the round trip time (RTT) for route $1 \rightarrow 4$, added to the amount of time used to setup processing, that is $5 \times t_{\text{setup}}$.. The RTT is the time that an electromagnetic wave takes to arrive at node 4 from node 1 and go back to node 1. Performing the same analysis for node 3 (hop one), the idle time is given by $t_{\text{DATA}}^{(3)} - t_{\text{PROCESS}}^{(3)}$, which is RTT added to $4 \times t_{\text{setup}}$. Using mathematical inference, the total idle time in a route from node *i* to node *j* is given by:

$$\delta_{\text{idle}}^{\text{OCS}}(i,j) = \sum_{k=0}^{H(i,j)-1} RTT(i,j) + 2H(i,j) \times t_{\text{setup}} + t_{\text{setup}} - k \times t_{\text{setup}}, \tag{1}$$

where $H(i,j)$ is the number of hops of the route from node *i* to node *j* and $RTT(i,j)$ is the round trip time between node *i* and node *j*.

Given c_0 as the speed of light, n_c as the core refraction index of optical fibers transporting the electromagnetic wave and $D(i, j)$ as the physical distance between nodes *i* and *j*, then $RTT(i, j)$ can be calculated as:

$$RTT(i,j) = \frac{2 \times D(i,j)}{v_p} = \frac{2 \times D(i,j) \times n_c}{c_0} \tag{2}$$

These results can be used to calculate the average idle time in a network. Therefore, assuming a topology with *N* nodes, the average network idle time for OCS paradigm, as described in Fig 1, is:

$$\delta_{\text{idle-net}} = \frac{\sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} \delta_{\text{idle}}(i,j)}{\sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} H(i,j)} \tag{3}$$

The parameter given by (3) is the average time that a resource in the network is made busy without being used for sending data. It is used to estimate the network load when considering an optical circuit switching paradigm.

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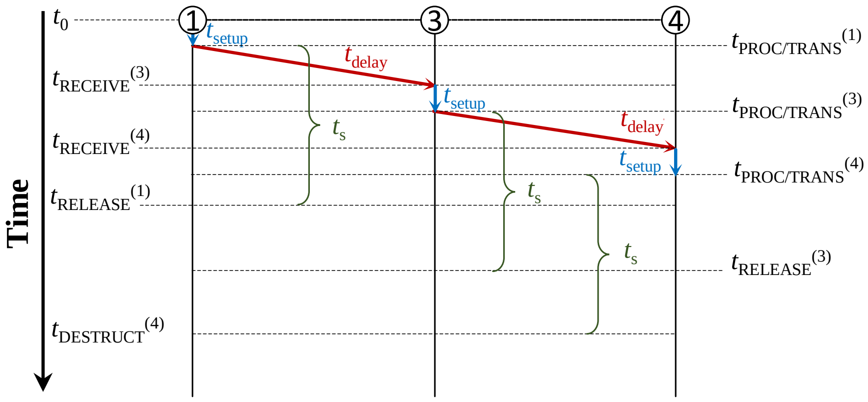

Fig. 2. Optical packet switching connection establishment.

B. *Optical Packet Switching*

Optical packet switching (OPS) uses a strategy that is similar to statistical multiplexing mechanism, on which the resource assignment is performed hop-by-hop. The required processing time to execute this task is generally gotten by means of fiber delay lines (FDL) and splitters. In OPS, the optical-to-electronic conversion of all the packet data is not necessary, but only the portion concerning the packet header (for routing information) [29]. Therefore, the processing is faster due to the usage of basic low rate electronics that is good enough to perform this task with the required time. On the other hand, the technological constraint to construct random access memories or to handle FDLs, the missing switching devices working in optical domain with ultrafast time responses, and the difficulties to implement efficient contention resolution schemes made OPS economically prohibitive around 15 years ago.

Nowadays, new switching devices and the progress in silicon photonics are making OPS interesting for some applications [19], like resources virtualization and data center networks [20]-[23]. Thus, the idle time for OPS is, in the worst case, the time taken to process routing information and to assign resources. This time is usually provided by an FDL with fixed storing time (t_{setup}). As previously assumed, given a route $1 \rightarrow 3 \rightarrow 4$, the signaling scheme to OPS is generically presented in Fig. 2. Beginning from t_0, all the information about resources at link $1 \rightarrow 3$ are processed. One single resource is chosen by node 1, sending data to node 3 after t_{setup} (at $t_{PROC/TRANS}^{(1)}$). In the worst case, which the assigned resource is made busy immediately after t_0, the average idle time for OPS is given by t_{setup}, since after $t_{PROC/TRANS}^{(1)}$ the optical packet is completely delivered at $t_{RELEASE}^{(1)}$ (after service time (t_s) from $t_{PROC/TRANS}^{(1)}$).

Consequently, assuming an automated data detection, the reserved resource and switching ports are released, at node 1, t_s time units after $t_{PROC/TRANS}^{(1)}$ ($t_{RELEASE}^{(1)}$). In addition, the resource is chosen in the first node and, if the chosen resource is not available in any link along the route, the optical packet is dropped. Note that all the nodes behaves in the same way.

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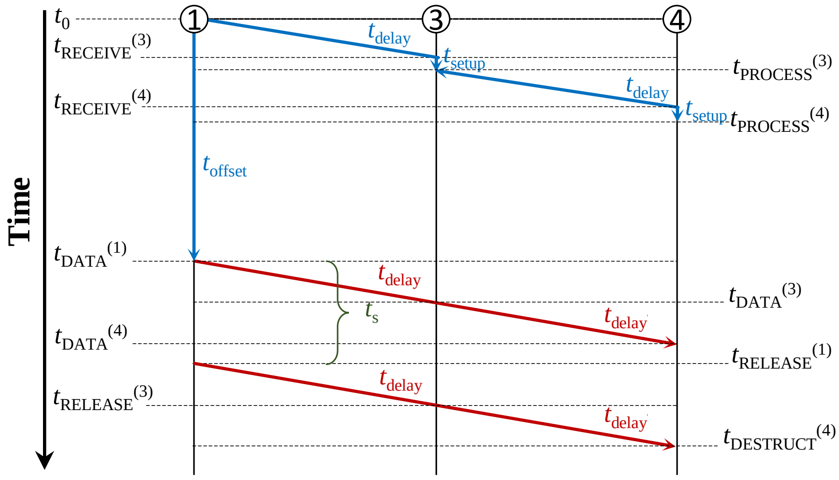

Fig. 3. Optical burst switching connection establishment.

Therefore, assuming any topology, the average network idle time, $\delta_{\text{idle-net}}$, for OPS paradigm, as described in Fig 2, is given by its node idle time:

$$\delta_{\text{idle}}^{\text{OPS}} = t_{\text{setup}} \tag{4}$$

C. *Optical Burst Switching*

A hybrid solution between OCS and OPS is known as optical burst switching (OBS) [16], since the data to a given destination node is aggregated in a burst and sent only after enough time to reserve the resources along a given path, which must be assigned in advance. Before sending a burst, a signaling message is sent through a control channel along the path in order to perform the resource reservation and setup the switching ports on each node. Some strategies for reservation, such as Just-in-Time (JIT), Horizon and Just- enough-Time (JET) were proposed, with their advantages and disadvantages concerning computational complexity and idle times discussed in [30]. In all signaling methods for OBS, resource reservation needs an offset time (t_{offset}), calculated as the minimum amount of time to provide all the resources reserved at destination node. On each node, a setup time (t_{setup}) is necessary to process the signaling message and to reserve the resources, but differently from OPS, the data information is received later and an optical memory is not necessary. Fig. 3 shows the signaling steps for JIT mechanism, which is adopted in the present work and carefully described in [30]. Therefore, before a burst is sent along the route $1 \rightarrow 3 \rightarrow 4$, it is stored by t_{offset} time units. During this time, a signaling message is sent along the path, carrying all the information about the burst, including its time length. Therefore, the signaling message negotiate network resources on each node for a specific period, enough to serve the burst. According to Fig. 3, when signaling message gets to node 3, at $t_{\text{RECEIVE}}^{(3)}$, it tries to assign the same resource which was assigned by node 1, at t_0. If the specific resource is not available, the reservation process fails and the burst is dropped when getting to node 3. Given JIT mechanism, the resource remains reserved for the period $t_{\text{PROCESS}}^{(3)}$ up to $t_{\text{RELEASE}}^{(3)}$. As previous switching methods, it is assumed an automatic data detection to release the reserved resource when stopping sending data (end of burst). Note that, in this example, resources belonging to

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node 3 are reserved for the given burst only up to $t_{\mathrm{RELEASE}}^{(3)}$, which means node 3 can reserve the same resource for any other burst after this time. Moreover, it is clear from Fig. 3 that the idle times are different depending on the position of nodes along the route. For instance, node 1 presents an idle time exactly equal to t_{offset} while node 3 presents an idle time of $t_{\mathrm{PROCESS}}^{(3)} - t_{\mathrm{DATA}}^{(3)}$. Thus, average idle time depends exclusively on the position that the node occupies in a given route. Assuming OBS with JIT signaling, the average idle time is given by:

$$\delta_{\mathrm{idle}}^{\mathrm{OBS\text{-}JIT}}(i, j) = \sum_{k=0}^{H(i,j)-1} t_{offset} - k \times t_{\mathrm{setup}} \tag{5}$$

Taken a network topology with N nodes and substituting (5) in (3), it is possible to calculate the average idle time for a whole network operating with OBS and JIT. Clearly, if other reservation mechanism are employed, the idle times can be slightly different, but the overall process is always the same. The knowledge of idle times of any switching paradigm and/or reservation mechanism is a key issue to calculate the network load, which has a difference from traffic intensity, as addressed in the next section.

III. The Network Performance Parameters

Some interesting parameters can be used to measure the performance of a conventional optical network. It is not different when analyzing a hybrid-switching optical network, since some characteristics of a specific switching paradigm can heavily contribute to the network behavior. In order to simplify the text, the generic term connection is used to refer to a lightpath in OCS, to an optical packet in OPS, or to a burst in OBS. Firstly, network load must be defined to avoid misunderstandings with traffic intensity.

A. Network Load and Traffic Intensity

The network load take into account the network stress due to idle resources. Consequently, the switching idle times are required to compute the overall network load. On the other hand, traffic intensity is the net load, effectively used to transport data information.

In general, the network load is defined as:

$$\rho = \lambda \times H\left(\frac{1}{\mu} + \delta_{\mathrm{idle\text{-}net}}\right), \tag{6}$$

where λ is the average arrival rate of connections (following a poissonian statistical distribution) and μ is the average departure rate of connections (following a negative exponential distribution), on which $1/\mu$ is the average service time (t_s). In addition, the parameter $\delta_{\mathrm{idle\text{-}net}}$ is the average network idle time, computed by (3), and H is the theoretical average number of hops, since the same connection can occupy a given resource in several links of the network.

The last relation presents an important issue for modeling and simulating an optical network, since it brings information about the value for the average arrival rate to have a given network load, assuming a topology with average number of hops H, a switching paradigm with network idle time

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$\delta_{\text{idle-net}}$ and mean service time of t_s. Note that, if somebody wants to approach the analysis with the traffic intensity, the term of average idle time must be eliminated from (6). In this case, performance parameters will show the differences between the network load and traffic intensity approaches. The most known performance parameter is the blocking probability; therefore, some issues on its calculation must be addressed.

B. Blocking Rate, Blocking Probability and Service Blocking Probability

The blocking probability is an issue that frequently has two approaches when considering an optical network. The first approach is assuming the blocking probability as the blocking rate, which is the number of blocked connections divided by the total number of generated connections. Although the blocking rate can be used as a performance parameter, it is different from blocking probability. The blocking probability should consider the opportunities of blocking along a route. For instance, route 1 → 3 → 4 in Figs. 1 to 3 has two links and, independently of the switching paradigm, the used resource to serve a connection in this route must be available in both the links. Clearly, this example shows that always there are two opportunities to block a connection using this route. Consequently, there are two important measures to compute the blocking probability: the number of blocking events and the number of links travelled (visited) by the connections. In order to provide an individual analysis for any switching parameter, they can be treated as a network service. Thus, assuming a network operating with S different switching paradigms, the number of blocking events can be stored in a vector B_s, for each switching paradigm s, $s \in [1{:}S]$. Similarly, considering a topology with L links, the number of link visits can be stored in a vector $V_{l,}$ for each network link l, $l \in [1{:}L]$. Therefore, the blocking probability for switching paradigm s is given by Pb_s:

$$Pb_s = \frac{B_s}{\sum_{l=1}^{L} V_l} \tag{7}$$

From (7), the network total blocking probability, concerning all the network switching paradigms can be computed by:

$$Pb = \sum_{s=1}^{S} Pb_s \tag{8}$$

Sometimes, it is interesting to compute the service blocking probability to compare the performance among network switching paradigms. To provide this parameter, the vector for link visits must store the information classified by switching paradigms, as shown by:

$$Psb_s = \frac{B_s}{\sum_{l=1}^{L} V_l^s} \tag{9}$$

Note that the relations (7) to (9) can be obtained also for blocking rate instead of blocking probability by replacing the vector V with a vector G_s, which stores the number of generated connections for each switching paradigm.

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C. Average Number of Hops

As the reservation process is quite different for each switching paradigm, another interesting parameter to evaluate the hybrid network is the real average number of hops. Assuming that each connection c, belonging to switching paradigm s, travels h_c links, the real average number of hops can be calculated by (10), for each switching paradigm s with number of generated connections G_s. It must be highlighted that for blocked OCS connections, h_c is always zero, since the connection does not effectively enter the network. On the other hand, OPS or OBS can travel a certain number of links before being blocked. Consequently, this number is always considered to compute the real average number of hops.

$$\bar{H}_s = \frac{\sum_{c=1}^{G_s} h_c}{G_s} \tag{10}$$

The real average number of hops can also be calculated for the network as a total average number of hops. In order to get this parameter, the average is computed over all switching paradigms, as given by:

$$\bar{H} = \frac{\sum_{s=1}^{S}\sum_{c=1}^{G_s} h_c}{\sum_{s=1}^{S} G_s} \tag{11}$$

The average number of hops can be considered as a metric to evaluate the physical resources and an estimative of power levels, considering the distribution of optical amplifiers.

D. End-to-end Average Delay

Following the same methodology used to get the real average number of hops, the real average end-to-end delay can be obtained. The end-to-end delay of each connection c is given by d_c in (12) and (13). As explained before, given a blocking event for OPS and OBS, d_c is stored with the end-to-end delay until the time that the blocking event occurred. Naturally, the real end-to-end average delay is dependent on the switching process and it can be calculated for a specific switching paradigm by:

$$\bar{D}_s = \frac{\sum_{c=1}^{G_s} d_c}{G_s} \tag{12}$$

The end-to-end average delay can be also calculated for the whole network as follows.

$$\bar{D} = \frac{\sum_{s=1}^{S}\sum_{c=1}^{G_s} d_c}{\sum_{s=1}^{S} G_s} \tag{13}$$

The end-to-end delay is a parameter that helps to evaluate the period of time that it takes, on average, to require the connection at the source node up to the time that it is received by the destination node. Consequently, it can be considered a valuable parameter to evaluate the type of

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switching paradigm compared to the required level of delay that the transported application can tolerate.

E. Average Utilization

Finally, the average utilization is another valuable performance parameter. This index is equal to unity if all the generated connections make all the network resources along all links busy, during a complete watching period. Thus, considering G_s connections of switching paradigm *s*, *L* links in the network topology with *R* available resources, and a watching time (simulation time) of t_{sim}, the average utilization for switching paradigm *s* is given by:

$$\bar{U}_s = \frac{\sum_{c=1}^{G_s}\sum_{l=1}^{L} t^r_{\text{hold}}(c,l)}{R \times L \times t_{\text{sim}}} \tag{14}$$

where $t^r_{\text{hold}}(c,l)$ is the time that connection *c* uses resource *r* at link *l*, with $r \in [1:R]$.

In order to have total information about average utilization, the network average utilization can be computed by:

$$\bar{U} = \sum_{s=1}^{S} \bar{U}_s \tag{15}$$

It should be clear that the utilization is an important parameter to provide information on how the network resources are being used by switching paradigms. Now that the details on switching paradigms are stated and performance parameters are defined, it is time to model the hybrid-switching optical network.

IV. The Hybrid-switching Optical Network

For the analysis of a hybrid-switching network, the calculation of the general idle time must have an adaptation, since there is a specific formulation for each kind of switching paradigms. Introducing a new network parameter as the traffic probability P_s, which is the probability of having, at any time, a traffic based in the switching paradigm *s*, the average idle time for a hybrid network can be stated as:

$$\delta^{\text{hybrid}}_{\text{idle-net}} = \sum_{s=1}^{s} \delta^{s}_{\text{idle-net}} \times P_s \tag{16}$$

In addition, the average service time is recalculated as function of traffic probabilities P_s, allowing getting the average arrival rate for a hybrid-switching network according to:

$$\lambda^{\text{hybrid}} = \frac{\rho}{H}\left[\sum_{s=1}^{S}\left(\frac{P_s}{\mu_s}\right) + \delta^{\text{hybrid}}_{\text{idle-net}}\right]^{-1} \tag{17}$$

As before, ρ is the network load and *H* is the theoretical average number of hops. If the traffic intensity approach is used instead of network load, then λ^{hybrid} must be calculated in the same way, just turning to zero the term concerning the idle time of hybrid network.

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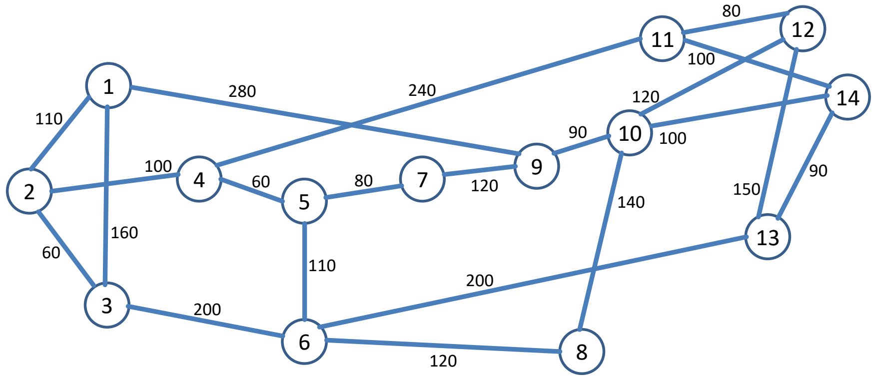

Fig. 4. NFSNet topology with 14 nodes and 21 bidirectional links.

The hybrid-switching model was incorporated to ONSim [31], an optical network simulator built in JAVA. ONSim treats all the phases of connection establishment and reservation processes for OCS, OBS and OPS as discrete events, according to schemes in Figs 1 to 3. The model and the simulation tool were tested on simple scenarios described by analytical formulations and on complex scenarios with known performance parameters, matching the results with statistical confidence higher than 98% by using 1 million connections per load value. The scenario that is used to achieve the results, concerning a hybrid-switching network, was comprised by three switching paradigms OCS, OPS and OBS, respectively described in their decentralized reservation processes by Figs. 1, 2 and 3. The adopted topology is a skeleton of NSFNet topology with 14 nodes and 21 bidirectional links, whose distances shown in Fig. 4. Routing process considered the shortest path distance, with just one fixed route for each source-destination node pair. In this case, the theoretical average number of hops is 2.2967. The connections are uniformly distributed by all possible node pairs. Moreover, it was assumed that any connection occupies a bandwidth of 25 GHz and that the available bandwidth is 150 GHz, shared for all of them, equivalent to 6 network resources (wavelengths) for ITU grid with 25 GHz channel spacing. This means that this bandwidth is sufficient to attend, on each link, up to 6 different connections. The characteristic of simulation scenario regarding the optical switching paradigm, traffic probabilities, service times, and idle times are given in Table I. These times were achieved from the reservation mechanisms of each switching paradigm and the propagation time was assumed as 5 μs/km.

Specifically for OBS, the offset time was assumed as 40 μs, while the setup time for all OCS, OPS and OBS was 5 μs. The time required by switching fabric to configure its switching ports was assumed as 2 μs in ONSim configuration, but it was not used for the present model. In order to keep, as far as possible, similar time scales for all the considered optical switching paradigms, service times for OCS and OBS were assumed as 10s and 2s, respectively. For OPS, it was assumed a service time of 1.6 μs, which is equivalent to an optical packet carrying 500 Bytes at 2.5 Gb/s or 2000 Bytes at 10 Gb/s. The average network idle times were computed using idle times for each optical switching

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TABLE I. PARAMETERS FOR OPTICAL SWITCHING PARADIGMS

Switching Paradigm	Service Time (s)	Average Network Idle Time (μs)	Traffic Probability	Average Holding Time (s)
OCS	10.0000000	27786.0	50 %	5.00138930
OPS	0.0000016	5.0000	20 %	0.00000132
OBS	2.0000000	0.3574	30 %	0.60000107

paradigm, given by (1), (4) and (5), respectively for OCS, OPS and OBS. The traffic probabilities were defined as function of a future possibility of deployment. The last column summarizes the average holding time for each optical switching paradigm. For instance, OPS has 5 μs of average network idle time and 1.6 μs of service time, which weighted for a 20% traffic probability means that OPS data units holds a resource, on average, for 1.32 μs.

Therefore, the data in Table I are used to compute the average arrival rate as function of network load, using (17). For instance, it can be seen that for a network load of 100 erlangs (E), λ^{hybrid} is 7.7732 arrivals/s. Note that in a hybrid-switching optical network, the assigned loads to each switching paradigm are different. Expanding (17) and isolating the load contributions of each switching paradigm for a given λ^{hybrid}, it is clearly seen that the distribution of network loads in the last example is 89.2883 E, 0.0001 E, and 10.7116 E, respectively for OCS, OPS and OBS. Now that the more important issues regarding the working of a hybrid-switching optical network were discussed, it is time to study this network as a function of the approached performance parameters.

V. RESULTS

All the performance parameters were calculated as function of network load, ranging from 10 E to 500 E, with intervals of 10 E, totalizing 50 points per curve. The first results are referred to blocking probability, which are shown in Fig. 5. The contribution of each switching paradigm on blocking probability, calculated by using (7), is shown in Fig. 5(a). The total blocking probability can be seen in this figure with a purple continuous line without markers, calculated by using (8). This figure shows that the major contribution for blocking probability is due to OCS, followed by OBS and OPS. Specifically, the OPS switching paradigm presents a high level of blocking, considering its low relative load. This behavior can be explained by the fact that the network available resources are shared by all the switching paradigms, and clearly OCS and OBS hold the resources for longer periods when compared to OPS. Thus, OPS suffers higher blocking probabilities because resource conversion is not possible and no contention resolution scheme are being used. Furthermore, the decentralized way to reserve resources for OCS makes all the available resources busy in the resource discovering process even if it will use just one of them. Since OPS is the most dynamical switching paradigm among the considered ones, it also suffers blocking probability.

The service blocking probability, calculated by using (9), was also achieved for the considered hybrid-switching paradigm, which is presented in Fig. 5(b). From this figure, the service blocking

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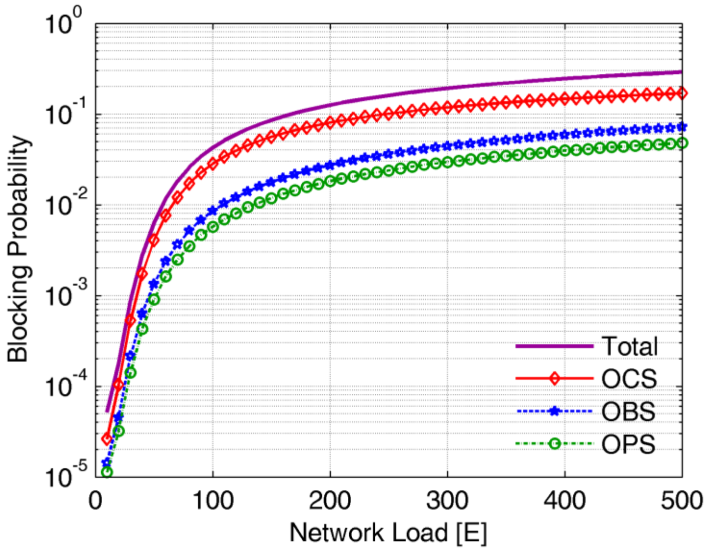
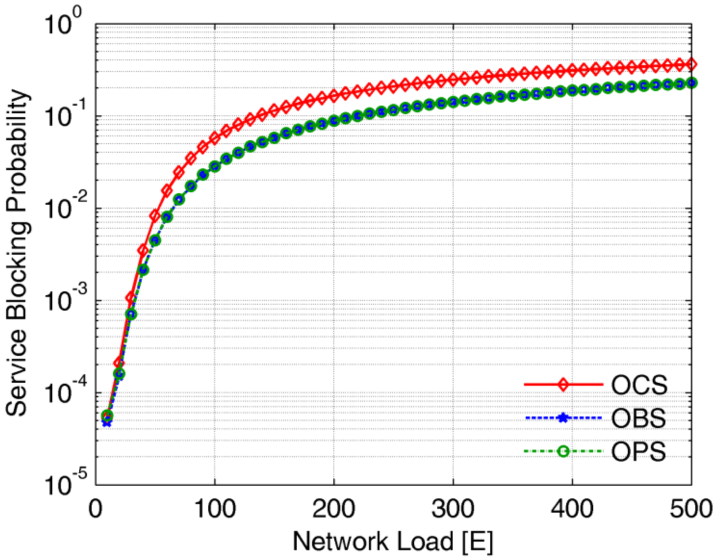


(a)



(b)

Fig. 5. (a) Blocking probability and (b) service blocking probability in a hybrid-switching network.

probability for OCS is clearly higher than the one for OBS and OPS, while OBS and OPS present approximately the same results (the curves for OBS and OPS are nearly overlapped). This behavior can be explained by using the results from Fig. 5(a), that show a blocking probability around 50% higher for OBS compared to OPS. Observing that the denominator of (7) is the same for any switching paradigm, it can be concluded that the number of blocking events for OBS is about 50% higher when comparing to OPS. On the other hand, the traffic probabilities, which were defined as 30% for OBS and 20% for OPS, influence the OBS and OPS values in the vector of link visits by a difference of around 50%. Clearly, this behavior will conduct to the same value when analyzing the service blocking probability, which is seen in Fig. 5(b).

Beyond the blocking probabilities, it was also analyzed three other network parameters that are important to the definition of general network performance. One of them is the evolution of the real average number of hops, calculated for switching paradigms and for the whole network by using (10)

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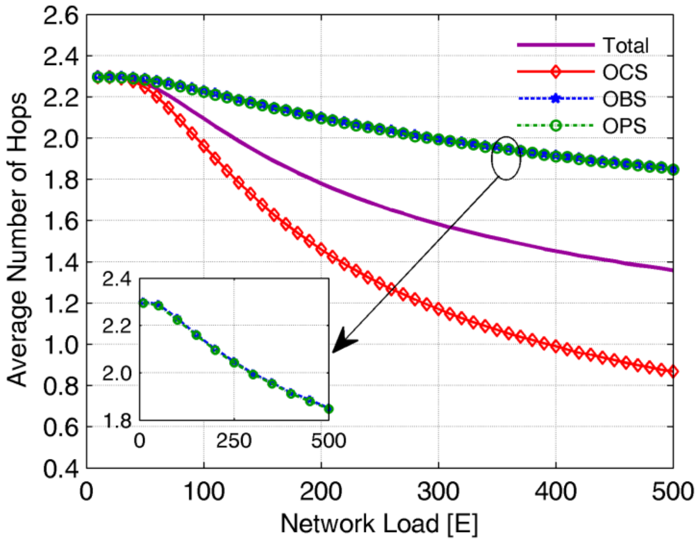

Fig. 6. Average number of hops in a hybrid-switching optical network.

and (11), respectively. Another one is the end-to-end average delay, calculated for switching paradigms and the whole network, by using (12) and (13), respectively. The last one is the evolution of average utilization, calculated for switching paradigms and the whole network, by using (14) and (15), respectively.

Fig. 6 shows the evolution of the real average number of hops. The purple curve without markers gives the average network results and the other curves show the considered switching paradigms. It can be seen that all curves start from the theoretical average number of hops (2.2967) and decrease to lower values due to blocking events and the facts that, as network load increases, the connections that travel smaller routes present more chances to get their final destinations.

On the analysis of switching paradigms, it is seen that the real average number of hops for OCS has a sharp decreasing in the average number of hops, while OPS and OBS have almost the same results, even considering the zoom view of this parameter in the inset figure. This result is in accordance with service blocking probability shown in Fig. 5(b). As previously discussed, the number of blocking events is around 50% higher for OBS comparing to OPS. As both paradigms are based in a hop-by-hop reservation scheme, the sum over the number of hops should follow the same proportion of blocking events. Consequently, as the number of traffic requests for OBS is 50% higher, the average number of hops for both OBS and OPS are nearly the same for this network scenario. It should be highlighted that optical bursts or optical packets are considered for these statistics only when they occupy at least one resource in any link of the network. In other words, an optical burst (or optical packet) is not considered for network statistics if no resource can be reserved for it at source node.

An interesting result regarding OCS is that from 400 E, the average number of hops decreases to smaller than one. This result shows that there are too many connection requests that collect free resources along a route, but they are not able to find a free resource along their routes (wavelength

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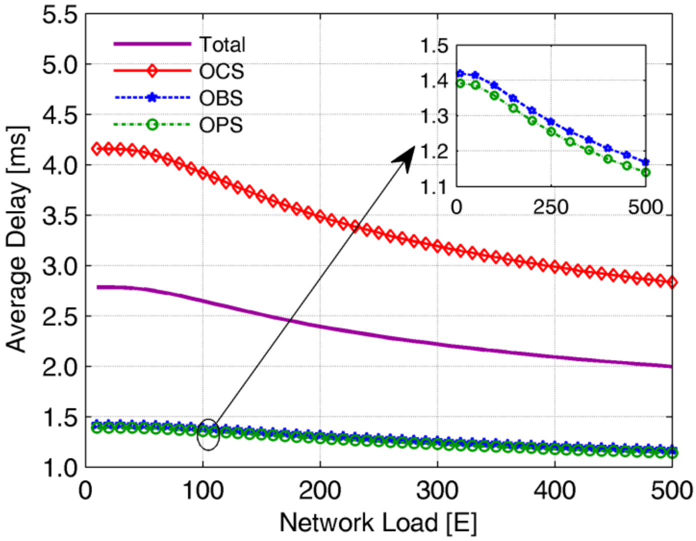

Fig. 7. Average delay in a hybrid-switching optical network.

continuity constraint). In this case, the request is blocked, but the zero hop travelled by the connection itself (not by signaling) is computed to the average number of hops statistic.

The results concerning the average delay are shown in Fig. 7. As before, the purple curve without markers brings the average network results. The other curves depict the considered switching paradigms. The results for OPS begin from 1.391 ms and provide information on the delay due to electromagnetic wave propagation, since the setup time of 5 μs per node does not have a considerable contribution to the end-to-end delay. These results are very similar to the results concerning OBS, but there is a tiny quantitative difference (that can be seen in the inset figure), since the OBS has an initial offset time that is generally larger than the sum of setup times in routing nodes. Analyzing the OCS case, in which for the effective transmission the signaling message must depart from source node, arrive at destination node, and go back to source node. Moreover, data information must travel from source node to destination node, and so the end-to-end delay should be approximately three times the average delay for OPS, added to setup times. For the low load region, the achieved results match very well with the expected results, since for 10 E, the network average delay of OCS is 4.157 ms. The strong decreasing in average delay after 50 E is supported by the level of blocking probability shown by Fig. 5.

Finally, Fig. 8 shows the results on average network utilization. The purple curve without markers brings the results on total utilization and it ranges from 3.9% to 65.7% of resources utilization taking the network load variation from 10 to 500 E. For the specific switching paradigms, OCS uses 52.34% of the available resources at 500 E and OBS uses 13.36%. On the other hand, OPS uses only 0.01% of the available resources when the hybrid-switching network is loaded with 500 E. This last result cannot be evaluated as unexpected, since the specific load due to OPS paradigm is

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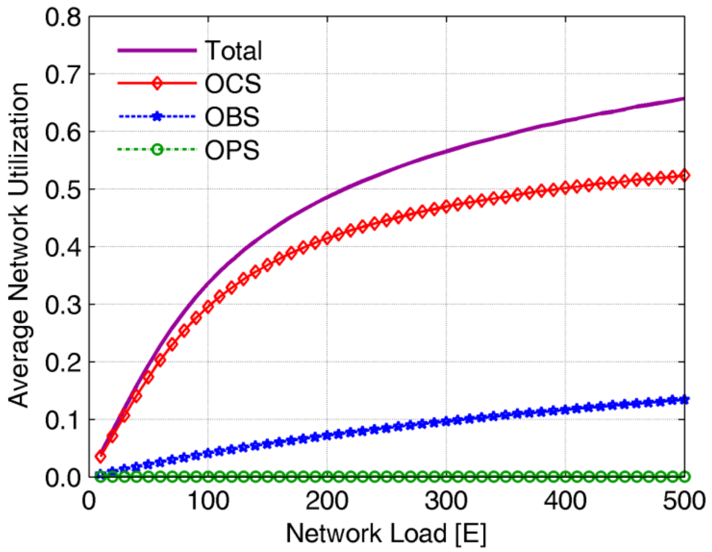

Fig. 8. Average network utilization in a hybrid-switching optical network.

significantly low. Therefore, all the presented results for the adopted scenario of a hybrid-switched optical network are coherent and support themselves.

VI. Conclusions

The present paper has addressed some issues on the modeling of an optical network working with hybrid-switching paradigms. The achieved results show that different switching paradigms can determine different results in performance, since they treated the network resources with very particular ways. The network model was deeply discussed and it can be adapted to study an elastic optical network working with hybrid-switching paradigms. In the future new studies, other distributions for traffic probabilities will be carried on. Moreover, other reservation strategies for OBS and OCS will be implemented. The presented study considered a scenario with resource sharing and decentralized signaling way. However, resource partitioning and even a centralized resource reservation can also be considered as a strategy to manage the occupation of network resources, considering a migration to elastic network paradigm, always pursuing to postpone the capacity crunch of optical network resources.

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